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ANTENNA SOLAR ENERGY TO ELECTRICITY CONVERTER (ASETEC)

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Generally, antennas are thought of in collecting audio, video, and data signals, which are processed and converted to intelligent data. However, using the same principle at higher frequencies, the antenna absorption theory appears to apply. To use this principle, the development of the antenna array will require expertise in the area of crystal growing (vapor deposition, sputtering, sintering, etc.) in micro circuitry and photo-lithography to make the antenna array and proper interconnections. The antenna configuration at lower (microwave-range) frequencies substantiated theoretical predictions of the antenna absorption theories with slight modifications.

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EXECUTIVE SUMMARY

A. Objective: Investigate the feasibility of using antennas for conversion of solar spectrum energy into electricity.

B. Background: Energy research laboratories have focused on converting solar energy to electricity by means of solid-state (P-N junction) techniques. Using this approach, the conversion efficiency appears to be severely restricted. Many quanta in the solar spectrum do not have enough energy to free electrons; others have more energy than is needed, and the excess is wasted. In the latter case, the excess energy produces heat and reduces the conversion efficiency.

C. Scope: It was necessary to identify how the wave and energy characteristics followed the absorption theory in the microwave range. From this we determined that the antenna theory must be modified for predicting design and performance of Antenna Solar Energy to Electricity Converter (ASETEC) systems. The indications are that a closer spacing of the converter elements (as predicted by the absorption theory) gives the highest power conversion.

D. Methodology: Started in the microwave range so that the geometric shapes would be large enough to control and manufacture to specifications in order to investigate the absorption theory. The frequencies used were .2 to 100 GHz.

E. Test Description: A receiving antenna, using a modified dipole design, was set up to receive microwave energy and convert it to electricity. This energy was sent to a spectrum analyzer with a display unit to determine the frequency and wave characteristics of the power transmitted. It was transmitted to drive a small DC electic motor which turned at 420 rpm. The total system efficiency was 65 percent.

F. Results: Upon completing the microwave testing, we demonstrated that tetrahedral silicon carbide (SiC) structures would convert solar energy to electricity. Wire screens were used as collector electrodes to cover more crystals (non-conductors). By shining a flood light on the 3" x 3" electrodes, 400 millivolts of electricity was produced.

G. Conclusion: This technology needs further investigation to determine the most cost effective materials and the optimum receptor configuration.

H. Recommendation: This technology appears to have a greater possibility of high efficiency than solid-state devices, making development desirable. With promise of high efficiencies, ASETEC would have important applications, such as wireless power transmission and remote-site power and may be used as radar-absorbing surfaces.

PREFACE

This report was prepared by Solar Energy Laboratory, University of Florida, Gainesville, FL, 32611, under contract number F08635-83-C-0136, for the Air Force Engineering and Services Center, Engineering and Services Laboratory (AFESC/RDCE), Tyndall AFB, FL 32403-6001.

This report summarizes work done between October 1986 and December 1987. HQ AFESC/RDCE Program Manager was Thomas C. Hardy.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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LIST OF SYMBOLS

The symbols and nomenclature are presented here in the order in which they appear in the text. Self-explanatory symbols are not listed here.

$E\lambda$	Energy at Wavelength λ
C	Constants
λ	Wavelength
e	Base of Natural Logarithm
T	Abosolute Temperature
P	Power
A,B	Constants
y	Parameter (lumped)
∞	Infinity
!	Factorial
σ	Stefan-Boltzmann Constant
F	Configuration Factor
β	Configuration Function
'	(Prime) Refers to the Variable Divided by b
ρ	Reflectivity
I_D	Direct Radiation
I_d	Diffuse Radiation
α	Absorptivity
τ	Transmissivity
~	Indicates Vector Quantity
$\tilde{E}$	Electric Field
ω	Angular Velocity of Wave
μ	Magnetic Permeability of Medium
$\tilde{H}$	Magnetic Field
ε	Dielectric Constant of Medium

$\tilde{A}^H$	Magnetic Vector Potential
$\tilde{A}^E$	Electric Vector Potential
ρ, ϕ, z	Coordinates
J_n	Bessel Function of Order n
k	$k^2 = \omega^2 \varepsilon\mu + \gamma^2$
γ	Propagation Constant
r	Radius of Dielectric Rod
x	kr

SECTION I

INTRODUCTION

A. OBJECTIVE

The objective of this research investigation is to show the feasibility of converting electromagnetic radiation into electricity at efficiencies higher than those predicted theoretically and obtained experimentally by solid-state theory and solid-state devices.

B. BACKGROUND

Before solar or electromagnetic wave energy can be converted it must be absorbed. Since the early 1950's, the Solar Energy and Energy Conversion Laboratory of the University of Florida, has investigated the phenomenon of surface absorptivity. A way to control absorptivity is by varying collector surface geometry.

After the energy (solar energy or electromagnetic wave energy at other wavelengths) is absorbed it can be converted into other forms.

Most of the energy used is in the form of heat, so this is the most important conversion. The end product, heat, can be used for water heating, space heating and cooling, swimming pool heating, water purification through distillation, cooking and baking, driving engines, and giving mechanical energy for its applications (driving machinery, pumping, driving electric generators, etc.), etc.

If electricity is the desired form of energy, it can be produced by mechanical systems driving electric generators, the most widespread use today. On the other hand, after the energy is absorbed, it can be converted to electricity in a more direct way.

At the present time solid-state devices (Solar Cells, etc.) are used for this direct conversion. Unfortunately, the conversion efficiency of these solid-state devices is severely limited. Since many of the quanta in the solar beam have more energy than is needed to free the electrons in the materials used, the excess is wasted. The longer wavelength quanta do not have enough energy to free electrons, and their energy is wasted. This analysis shows a maximum theoretical conversion efficiency of only 24 percent. Conversion efficiencies of up to 15 percent have been obtained, but more common is a 10 percent for solid-state devices.

C. APPROACH

This investigation used the theory that energy consists of electromagnetic waves rather than quanta, and utilizes antenna theory as much as possible. The duality-of-light concept allows this. The antenna theory does not exactly fit since its emphasis is on data, voice, video signal transmission, and collection but not power. A considerable amount of energy falling upon an antenna array designed according to the present theories, goes right through the array. Thus arrays are often put behind each other with reflector plates, etc. Nevertheless, the antenna theory allows a theoretical maximum efficiency of 100 percent.

Theoretically, with proper design and configuration, almost 100 percent of the beam energy can be absorbed. Direct

conversion to electricity is feasible if the geometric shapes are designed as antenna. Thus, much higher conversion efficiencies from solar energy to electricity should be obtainable by combining the results of the collection and antennae theories.

An interesting observation is that nature converts solar energy or portions of it (light) to electricity with antennae instead of solid-state devices (the rods and cones in the eye,insect antennae, etc.).

To investigate this approach it was decided to start in the microwave range of electromagnetic radiation, because the sizes, as determined by the wavelengths, are more easily manufactured and controlled. When the configurations are optimized, miniaturization would follow.

First, microwaves in the 0.2 to 3.0 GHz range were used because of the availability of equipment. This frequency range should be satisfactory since, according to theory, the electromagnetic wave behavior is not a function of wavelength. However, in this range of multiple wavelength configurations, the physical sizes became unmanageable. For this reason 10 GHz equipment was used, to allow these multiple wavelength configuration to be investigated. To evaluate the findings at higher frequencies, equipment available at 100 GHz was used, mainly to establish that the results obtained with lower wavelengths do not change appreciably with change in frequency.

Surface geometries and configurations forming antennae were designed as described in the report and experimentally evaluated, singly, as well as in arrays. Overall conversion efficiencies of over 60 percent from the electromagnetic wave to the desired output were obtained, showing conversion efficiencies much higher than the 10 or 15 percent of solid-state devices.

After the feasibility of this approach in the microwave range was established, a microwave beam in the laboratory was transmitted to a receiving antenna and the resulting electricity was analyzed, converted to DC, and used to drive a small motor.

To obtain some preliminary information on conversion behavior and characteristics at solar radiation frequencies, readily available geometries (though not ideal since the elements were randomly oriented) were used. Such a material was SiC used as grains in Carborundum® paper, a cheap and readily available configuration. Some of the desired characteristics could be investigated and the feasibility of converting solar energy to electricity by the antenna method established.

D. SCOPE

This report covers the feasibility of the investigation, with some optimization. Materials effects and metals versus dielectrics were investigated, so that optimum configurations, which combined crystal growing techniques with thin film technology and microelectronic circuitry, could be manufactured.

Although the ultimate objective of this investigation is to efficiently convert solar energy into electricity, power transmission and efficient absorption in the microwave range have many important applications. This method may be used to supply remote stations with beamed energy, both on the surface of the earth and in space. The efficient absorption of beamed energy, thus preventing reflection and consequent detection of the absorbing surface, is another application.

The report discusses the theories as they apply, presents the experimental results, evaluates them, and summarizes them in the conclusions.

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SECTION II

THEORY

Presently accepted theories predict that a body at a temperature above absolute zero emits energy by radiation. The energy emitted often acts like little particles or bullets and sometimes behaves like electromagnetic waves. This behavior is often referred to as the duality-of-radiated energy or, in the visible range, as the duality-of-light.

Both the particle or quantum concept and the wave conceptare needed to explain the natural phenomena. Historically, famous scientists have developed these concepts, with Newton as the particle proponent and Maxwell as the wave phenomena investigator.

The particle approach has developed into the Theory of Quantum Mechanics. Many of the available devices for the conversion of solar energy into electricity, such as the solar cell, are based upon that theory.

The wave characteristic and its implications have so far been neglected in the conversion of solar energy to electricity. They will be used here in the development of devices for the conversion process of solar energy to electricity. It is believed that this approach will yield efficiencies of conversion that significantly exceed the available devices.

The solid-state conversion theories have severe efficiency limitations; the antenna or wave conversion does not. Nature uses antennae, rather than solid-state devices in

converting solar energy to electricity. Because this process has worked over billions of years this theory merits serious consideration.

A. SOLAR, ELECTROMAGNETIC RADIATION

As mentioned earlier, any body above absolute zero temperature emits energy by radiation. This radiation is distributed between wavelengths from zero to infinity, having different intensities at different wavelengths. A peak will occur at a particular wavelength. The higher the temperature of the radiating body, the shorter the wavelength at which the peak occurs.

Three famous scientists (Wien, Reyleigh and Planck) worked out expressions for the distribution of these energies. They are:

Wien

$$E\lambda = C_3 \lambda^{-5} e^{-\frac{C_4}{\lambda T}} \tag{1}$$

Reyleigh

$$E\lambda = C_5 \lambda^{-4} T e^{-\frac{C_6}{\lambda T}} \tag{2}$$

Planck

$$E\lambda = \frac{C_1 \lambda^{-5}}{e^{\frac{C_2}{\lambda T}} - 1} \tag{3}$$

Planck's distribution, based upon his Quantum Theory, is the distribution accepted today.

Figure 1 presents the distribution for the sun's radiation. The dashed curve is the theoretical relative energy outside the atmosphere. The solid line represents the radiation as it arrives at the surface of the earth.

Figure 2 shows the experimental points, the accepted curve representing those points, and the theoretical curve. This graph and the information presented make comparison easy. This figure refers to conditions outside the atmosphere.

Planck's distribution make it easy to determine the energy or power radiated. It is represented by the area under the curve and can be obtained as follows:

$$P = \int_0^\infty \frac{C_1 \lambda^{-5}}{e^{\frac{C_2}{\lambda T}} - 1} \, d\lambda \qquad (4)$$

let

$$A = C_1$$

$$B = \frac{C_2}{T}$$

$$y = \frac{B}{\lambda}$$

then

$$d\lambda = - \left(\frac{B}{y^2}\right) dy$$

$$P = - \int_{-\infty}^{0} \frac{A}{B^4} y^3 (e^y - 1)^{-1} dy$$

$$= \frac{A}{B^4} \int_{0}^{\infty} y^3 (e^y - 1)^{-1} dy \quad . \qquad (5)$$

Expanding this expression into infinite series

$$P = \frac{A}{B^4} \int_{0}^{\infty} y^3 (e^{-y} + e^{-2y} + e^{-3y} + \ldots) dy \quad . \qquad (6)$$

Integrating term by term with the integral solution from Tables

$$\int_{0}^{\infty} y^n e^{-ay} dy = \frac{n!}{a^{n+1}}$$

$$\underline{P} = \frac{A}{B^4} \left(\frac{3!}{1^4} + \frac{3!}{2^4} + \frac{3!}{3^4} + \frac{3!}{4^4} + \ldots\right)$$

$$= \frac{A}{B^4{}_4} \times 6 \left(\frac{1}{1^4} + \frac{1}{2^4} + \frac{1}{3^4} + \frac{1}{4^4} + \ldots\right) \qquad (7)$$

and substituting original values

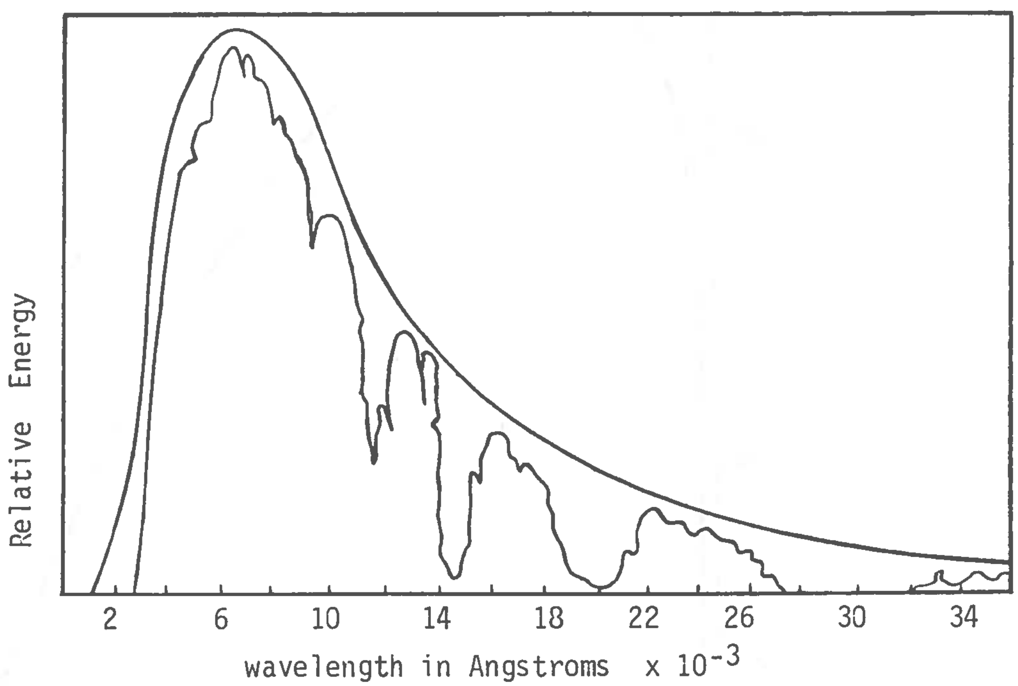


Figure 1. Relative Intensity of Solar Energy at Different Wavelengths

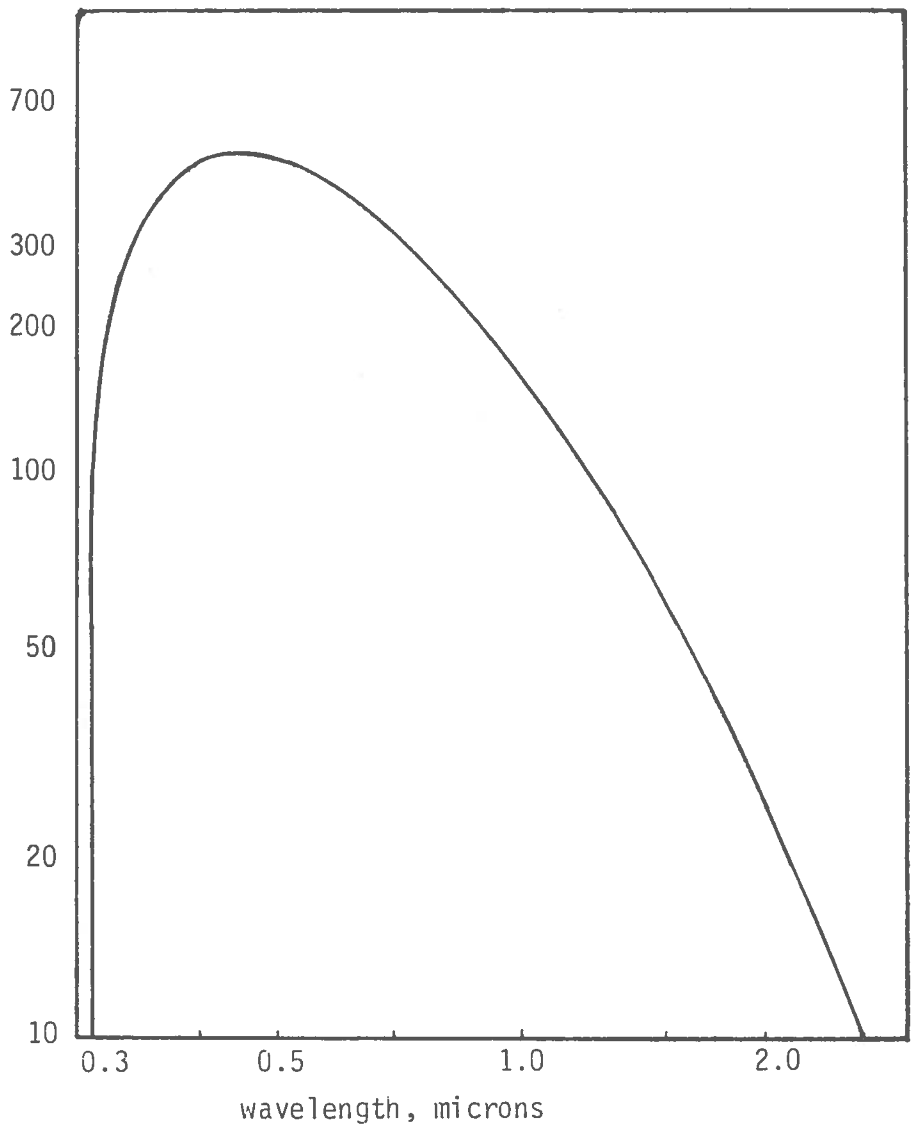


Figure 2. Proposed Standard Curve of Solar Radiation Outside the Earth's Atmosphere

$$= \frac{C_1 T}{C_2^4} \times 6 \left(\frac{1}{1^4} + \frac{1}{2^4} + \frac{1}{3^4} + \frac{1}{4^4} + \ldots \right)$$

$$= \sigma T^4 \qquad (8)$$

This last expression represents the power radiated by a body at a particular temperature.

If it is assumed that the surface temperature of the sun is 10,000° F (a number agreed upon by international consensus) the actual power radiated can be obtained, as well as its distribution.

B. NATURAL AND MANMADE ENERGY ABSORBING CONFIGURATIONS

After considering the characteristics of the radiation given off by the sun, or hot bodies in general, it is necessary to examine the natural and manmade configurations capable of absorbing this energy.

Nature's methods and designs are interesting. Figures 3 and 4 show scanning electron micrographs of various antennae used by the insects for communication in the infrared frequency band.

Closer examination of Figure 3 reveals a number of different designs and configurations. Straight cones like the one in the center showing large length over diameter ratios, cones exhibiting curvatures thus having nonsymmetrical characteristics, and even arrays, sometimes referred to as "picket fence," are all shown on the same insect.

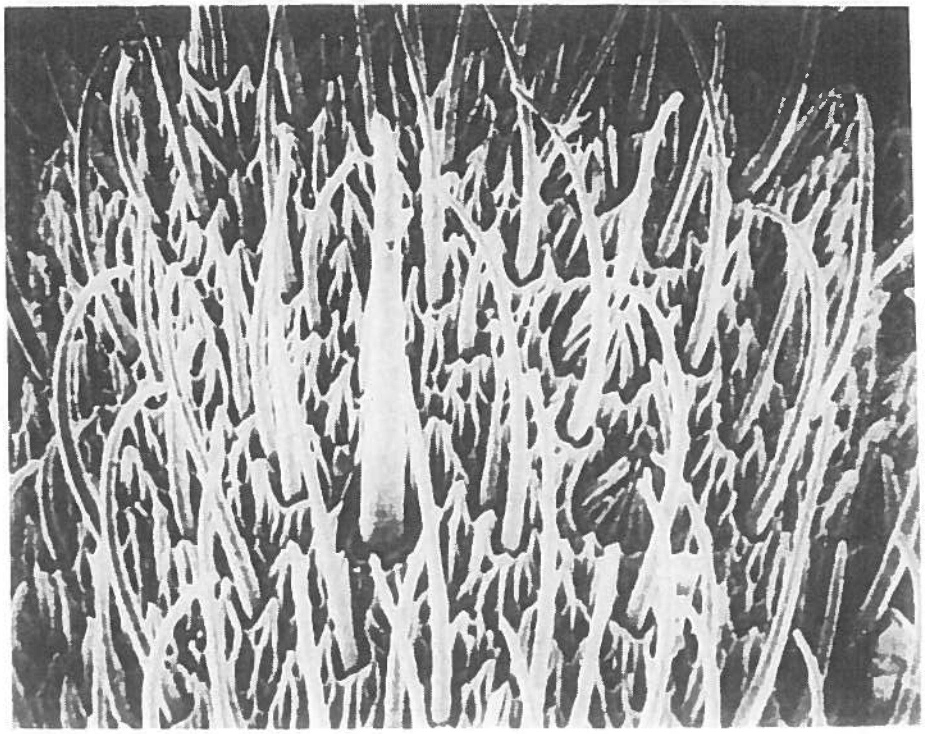


Figure 3. Scanning Electron Micrograph of Antenna Sensilla from Corn Earworm Moth

Figure 4, a larger magnification, gives more detail of the fine structure of a single main trunk antenna with small antennae mounted on the trunk. Also clearly shown is the base mounting of this natural-grown dielectric waveguide.

The detailed structure, for example a cone antenna of an insect, can be seen in Figure 5. Without going into great detail, a few major parts may be pointed out. The absorbing part or waveguide, A, the waveguide or antenna mount, B, the probe, K, and signal conductor or transmission line, E, form the necessary components of this electromagnetic wave absorbing system.

Many shapes, forms and configurations can be found in nature. Equivalent counterparts can be found in communication technology and practice. (Figures 6 and 7.) Almost every natural configuration finds its electrical counterpart, the main difference being that, in our technology, the antennae are usually made of metals, while nature constructs them from dielectric materials.

It must be pointed out that the insects use their antennae for communication, the manmade equivalent structures are also used for communication.

In the applications for communication, the objective is to have a design which absorbs one single frequency and discriminates against the others; in other words, it is tuned to the desired wavelength. Also, much of the energy in a beam will not be utilized by these systems. Power conversion requires antennae systems which respond to a wide range of frequencies and absorb as much of the energy in the beam as possible.

Energy absorption can apply to other designs and applications in our everyday technology. One such

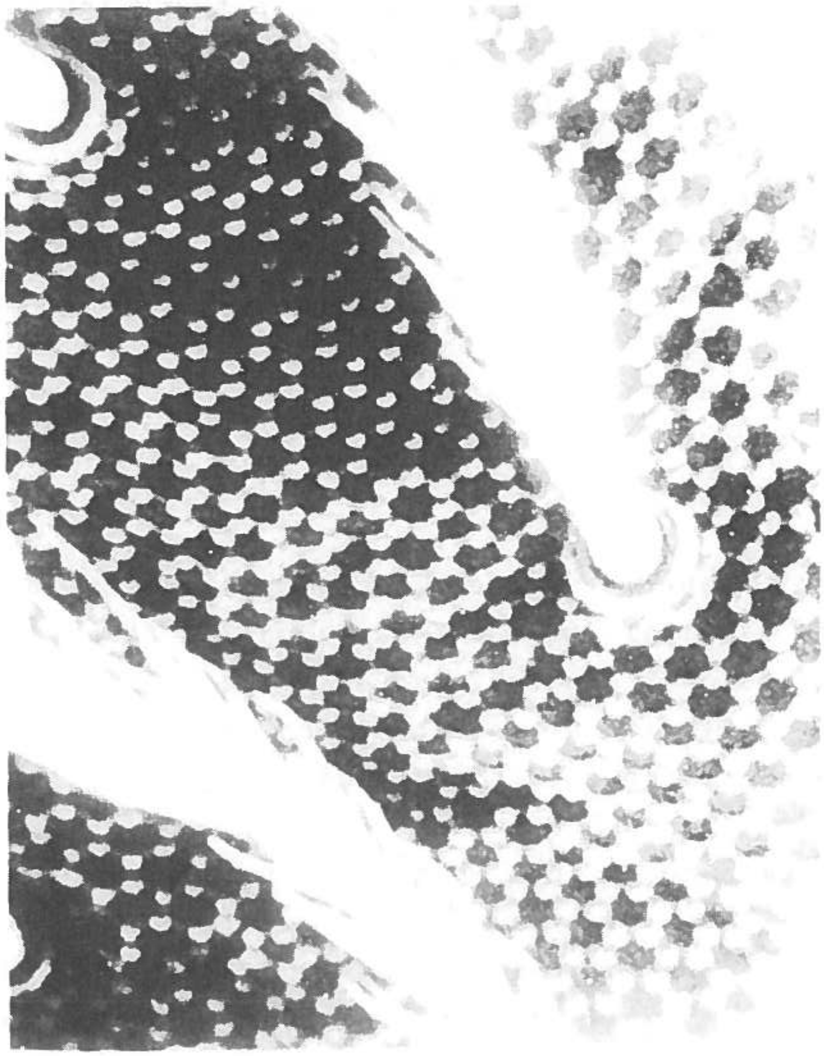


Figure 4. Greater Magnification Showing Fine Structure of Insect Antenna

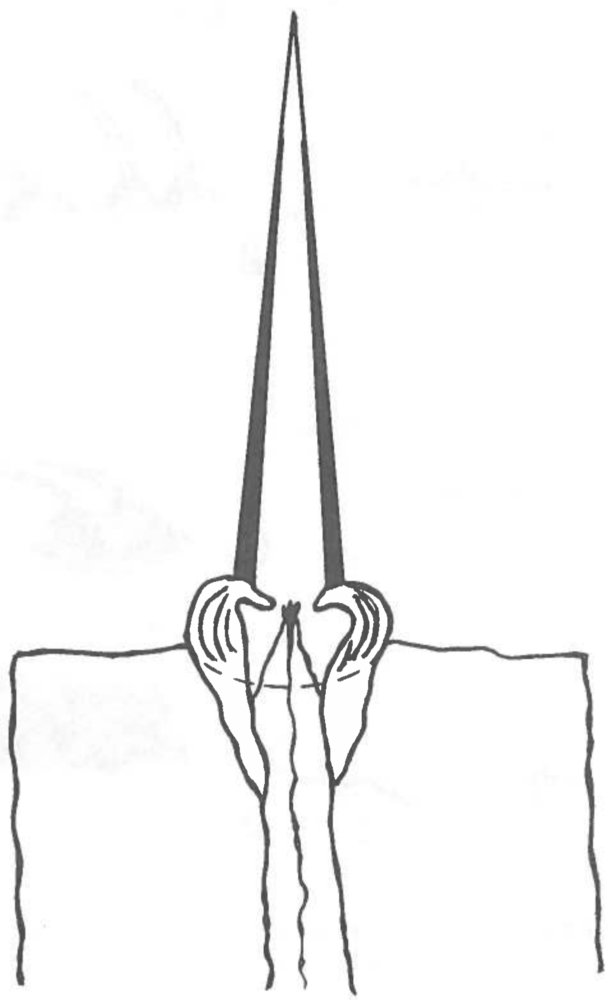


Figure 5. Construction Detail of Insect Antenna

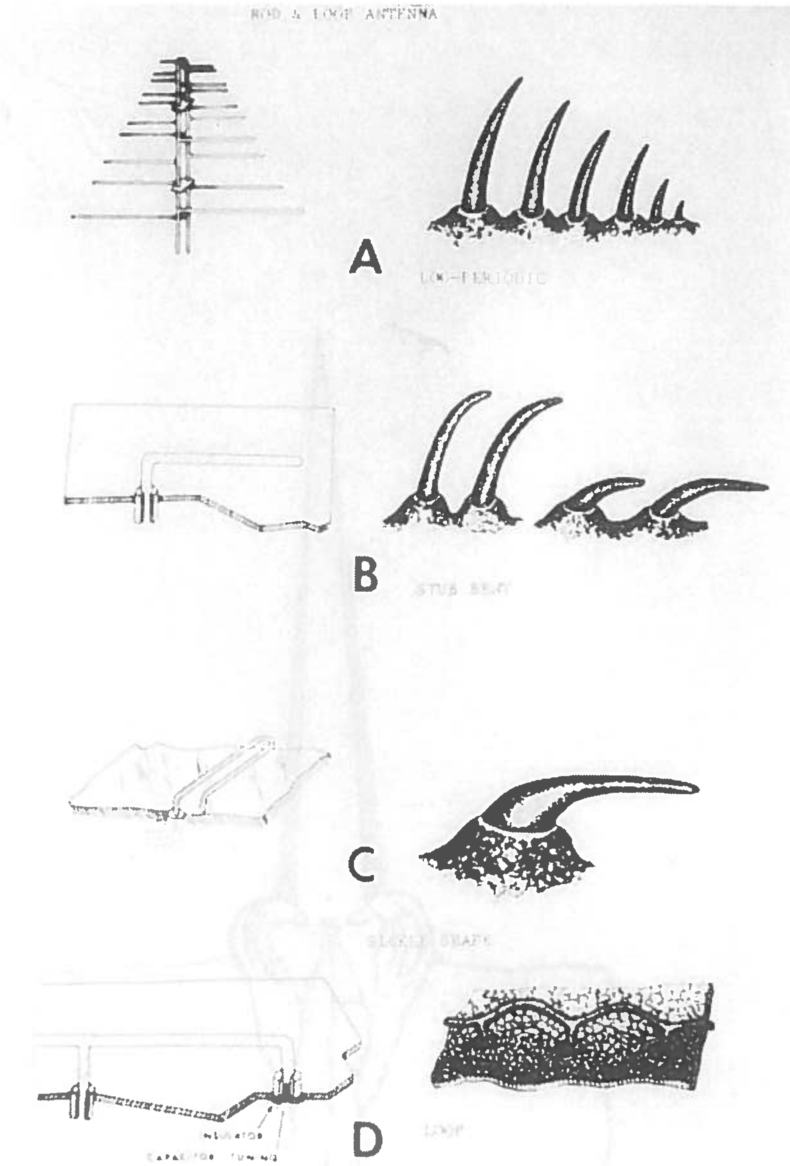


Figure 6 . Nature's Insect Antenna Designs and Manmade Equivalents

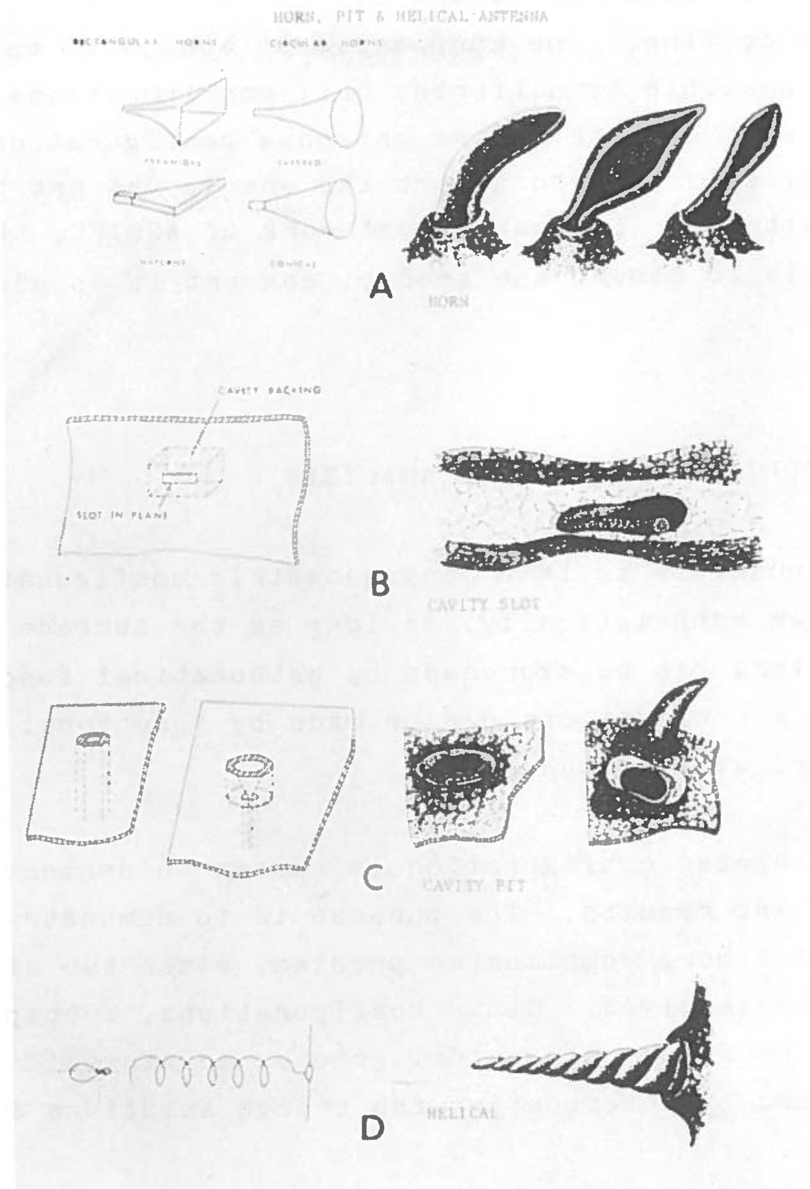


Figure 7. Nature's Insect Antenna Designs and Manmade Equivalents

application is shown in Figure 8. It is an anechoic chamber for engine testing. The purpose is to absorb as much sound energy as possible by different wall configurations. These look basically similar to the antennae configurations, but the objective is just to absorb the energy and not to do anything with it. In the present work of ASETEC, the objective is to absorb the energy, convert it to electricity and use it.

C. THEORETICAL MATHEMATICAL ANALYSIS

It is possible to take many geometric configurations and analyze them mathematically, as long as the surface configurations can be expressed by mathematical functions. Naturally, approximations can be made by functional fitting or by numerical approaches.

A rectangular configuration is chosen to demonstrate the procedures and results. The purpose is to demonstrate the solution of a more complicated problem, since two different surfaces are involved. Other configurations, V-shaped troughs or pyramids, sinusoidal grooves or sinusoidal peaks can be formed by intersecting the trough solutions at right angles, etc.

The example presented here results in surfaces which have rectangular grooves, and rectangular stumps resulting from these grooves intersecting at right angles.

The method presented here allows the determination of apparent reflectivities, absorptivities and, in some cases, transmissivities of geometric configurations, by theoretical means, when the material properties are known.

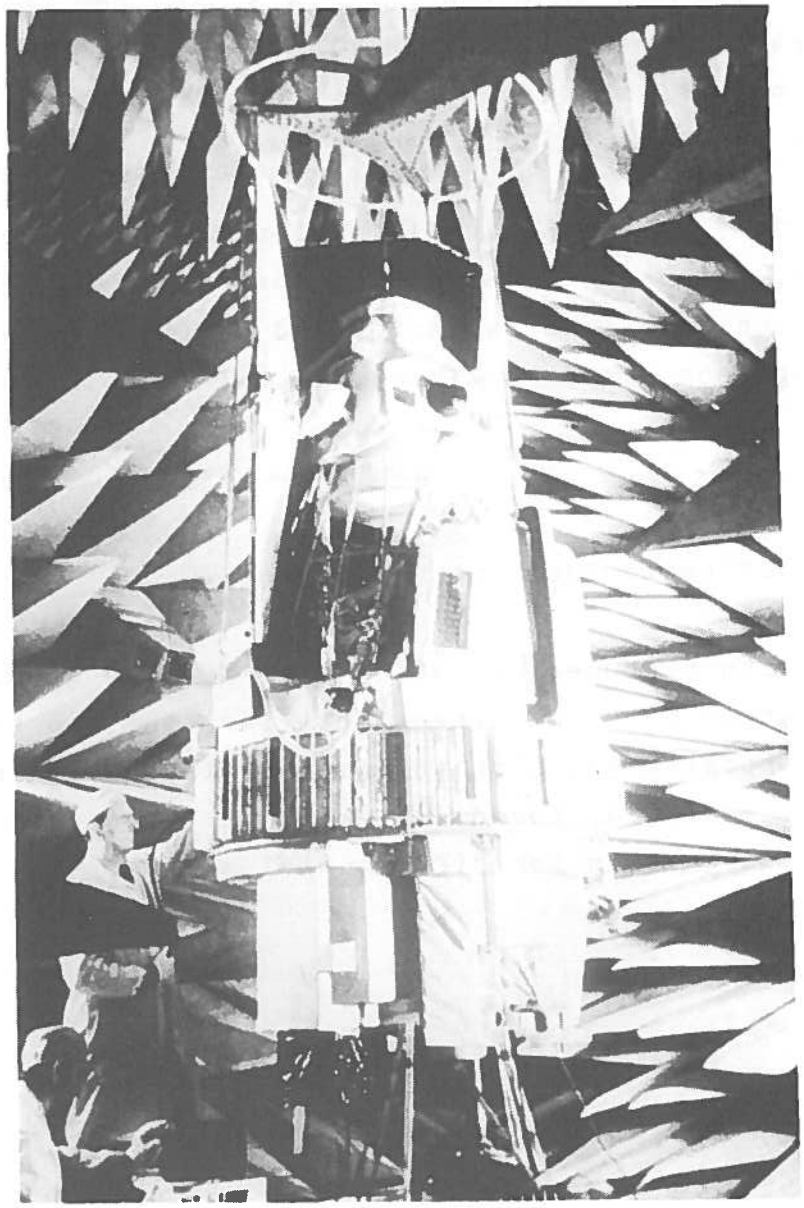


Figure 8. Anechoic Chamber for Sound Energy Absorption

It is assumed that the materials used for the actual configuration are diffusely reflecting. This is the case with almost all materials after they are exposed to the elements for a relatively short time.

Figure 9 gives the configuration for the theoretical analysis. Since the energy from the sun or other sources can arrive both as direct radiation and diffused radiation (arriving from all directions), both cases will be analyzed here.

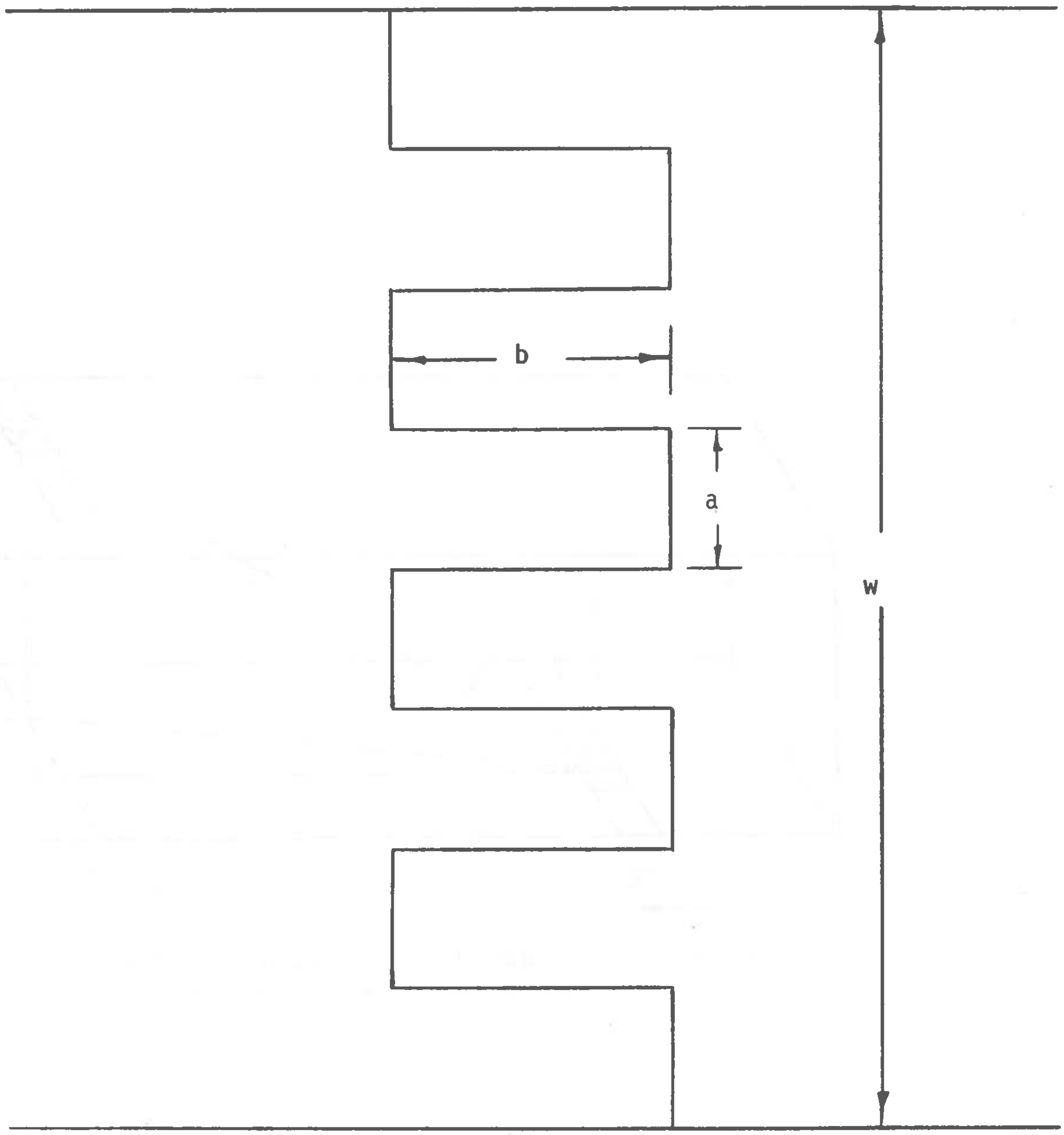
1. Diffusely Incident Radiation

With diffused radiation entering the geometric configuration from all directions, the configuration factor between opposite walls of the rectangular configuration can be evaluated for differential elements (Figure 10) and through integration for differential strips.

$$dF_{x_0 - x} = \frac{h^2\ dx}{2[h^2 + (x - x_0)]^{3/2}} \tag{9}$$

The same type of information between differential strips between the sides in perpendicular configuration is given in Figure 11. Again, the configuration factor for this case can be obtained in a manner similar to that for the parallel walls.

$$dF_{x_0 - y} = \frac{y x_0\ dy}{2[y^2 + x^2]^{3/2}} \tag{10}$$



$$\frac{l}{w} = 1 + \frac{b}{a}$$

Figure 9. Configuration for Theoretical Analysis

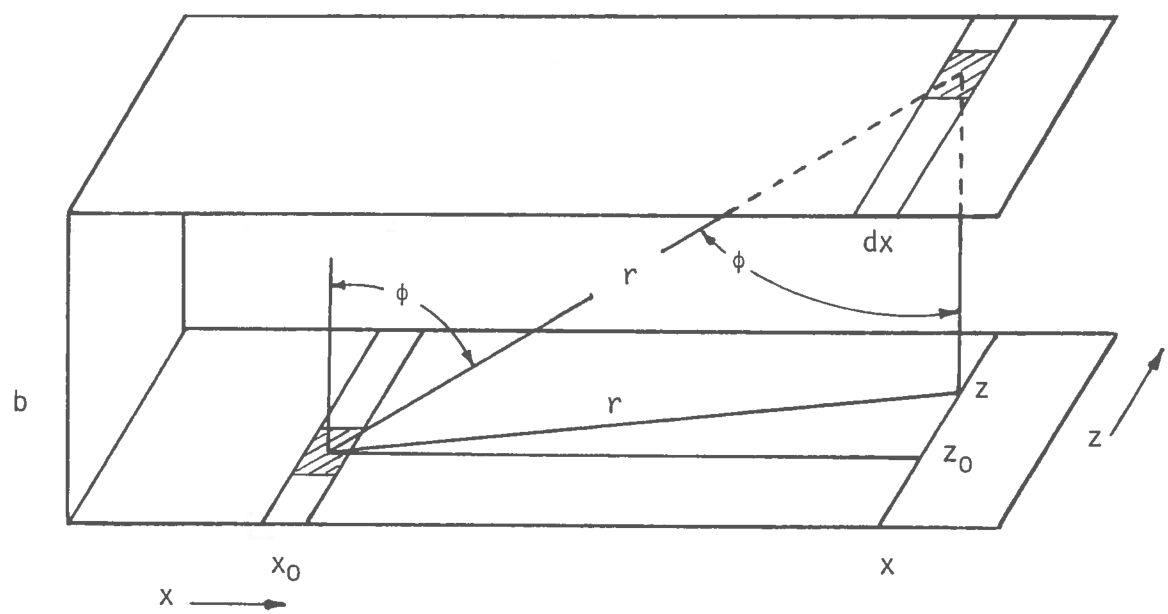


Figure 10. Geometric Configuration for Opposite Parallel Walls

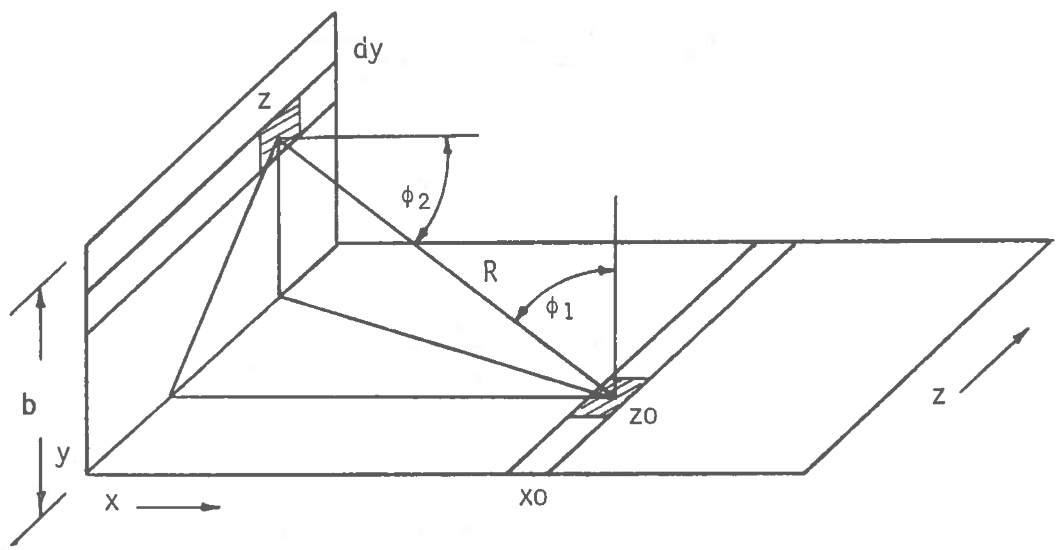


Figure 11. Geometric Configuration for Adjacent Perpendicular Walls

Having thus, calculated and obtained the Geometric Configuration Factors, (Equations (9) and (10)) it is now possible to obtain the Local Apparent Reflectivity of the configuration. To do this it is necessary to integrate over the total internal surfaces, or to solve the integral Equations (11A) and (11B).

$$\beta_a(x_0') =$$

$$\beta + (1-\beta)\left[\int_0^1 \beta_a(x') \frac{a'\ dx'}{2[a'^2 + (x' - x_0')^{3/2}}\right.$$

$$\left. + \int_0^{a'} \beta_a(y') \frac{y' x_0'\ dy'}{2[y'^2 + x'^2]^{3/2}}\right] \qquad (11A)$$

$$\beta_a(y') =$$

$$\beta + (1-\beta)\left[\int_0^1 \beta_a(x') \frac{y' x'\ dx'}{2[y'^2 + x'^2]^{3/2}}\right.$$

$$\left. + \int_0^1 \beta_a(x') \frac{(a' - y')\ x'\ dx'}{2[(a' - y')^2 + x'^2]^{3/2}}\right] \qquad (11B)$$

The procedure requires the assumption of a functional variation for $\beta_a(x')$, substituting this function into Equation (11B) and solving for $\beta_a(y')$. This result is then substituted into Equation (11A), which, in turn, is solved for $\beta_a(x_0')$. If this value, as well as all others for each x', falls into

the originally assumed function, the distribution of the local reflectivity in the configuration is obtained from Equation (11C).

$$\rho_a\ (x_0') = 1 - \beta_a\ (x_0') \tag{11C}$$

The prime (') in the above equations refers to the variable divided by the parameter b, the width of the fold.

When the reflectivity distribution is known, it is only necessary to sum or integrate over the whole grooved surface to obtain the apparent reflectivity of the groove. This value, averaged with the front reflectivity of the material, gives the apparent reflectivity ρ_d'' for the diffuse radiation. The results are plotted in Figure 12 in terms of the flat material reflectivities and the folding ratio.

Since one cannot expect to be so lucky as to assume the correct function for $\beta a(x')$ a great number of iterations are normally required, forming an ideal problem for a large scale computer.

2. Parallel-Ray Incident Radiation

In this case a portion of the material receives direct radiation while the rest receives only diffusely reflected radiation as previously analyzed. If it is assumed that the folds are at least as deep as wide, the procedure previously described can be followed. The nomenclature and configuration for this part of the problem are given in Figure 13.

The long computational work described previously contains the results shown in Figure 14 giving the apparent

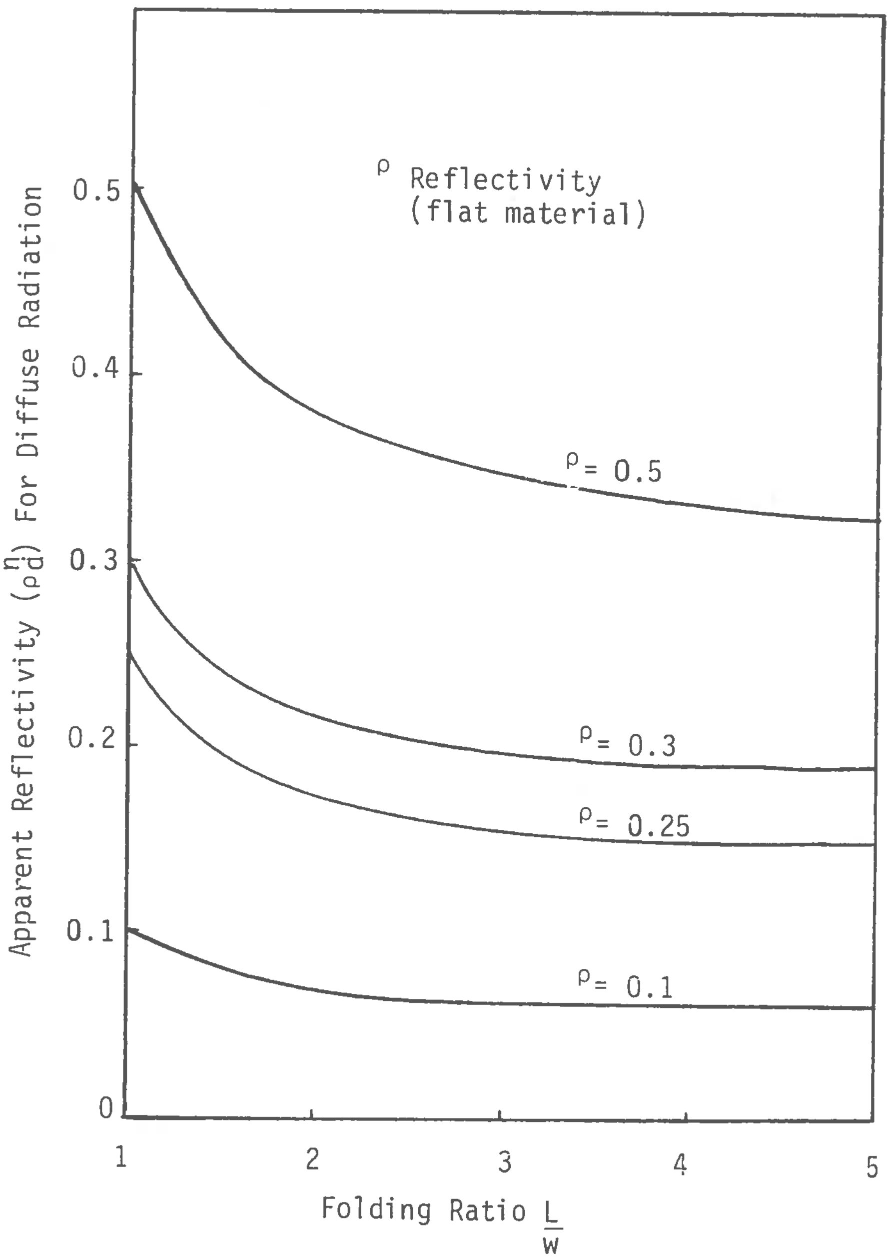


Figure 12. Apparent Reflectivities for Diffusely Reflecting Materials under Diffuse Irradiation (Rectangular Grooves)

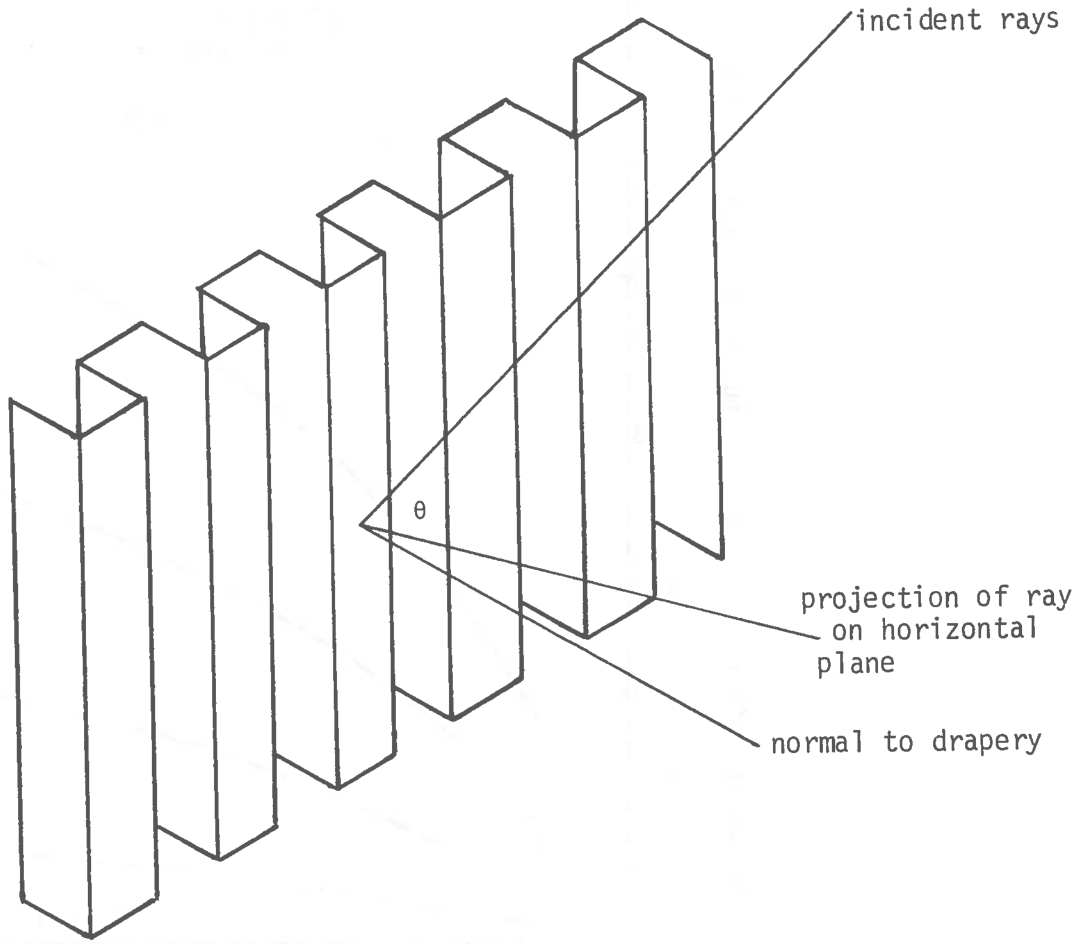


Figure 13. Configuration and Nomenclature for Analysis

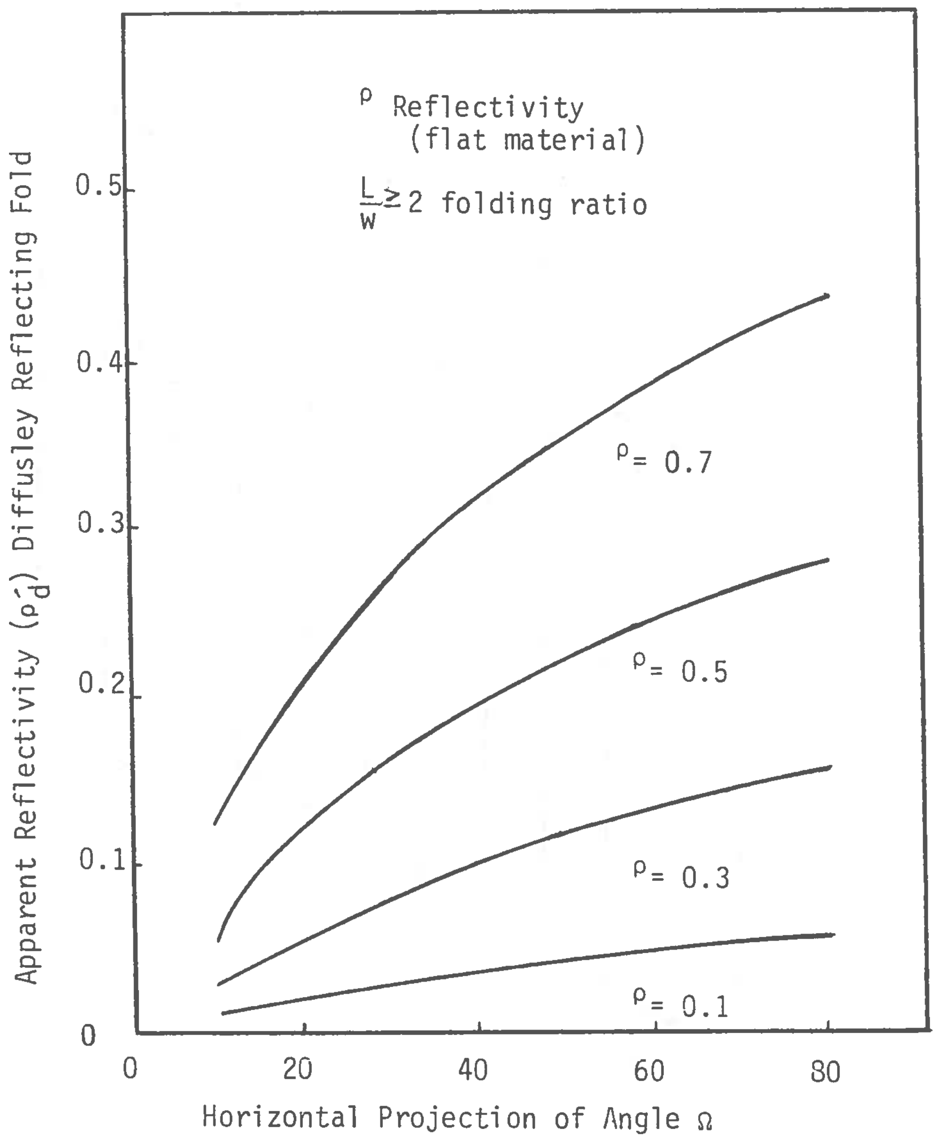


Figure 14. Apparent Reflectivity for Parallel Rays in Diffusely Reflecting Folds

reflectivity of the fold for direct-ray irradiation in terms of the flat material reflectivities and the horizontal projection of the angle of incidence.

The values of Figure 14, when averaged with the reflectivity of the front part of the material, give the apparent reflectivity ρ_d'' of the material as a whole for direct ray irradiation,

$$\rho_D'' = \frac{\rho_D' + \rho}{2} . \tag{12A}$$

The ratio of direct parallel ray irradiation to total irradiation is

$$\frac{I_D}{I_D + I_d} = F. \tag{12B}$$

With portions of direct and diffuse solar radiation (or other radiation) for any specific case known, the apparent refectivity ρ_a of the material is obtained from Equation (12C)

$$\rho_a = F(\rho_D'') + (1 - F)\rho_d'' . \tag{12C}$$

Some typical flat material reflecitivities for three different materials are given in Figure 15. They are the information needed in this analysis and are usually furnished by the manufacturer.

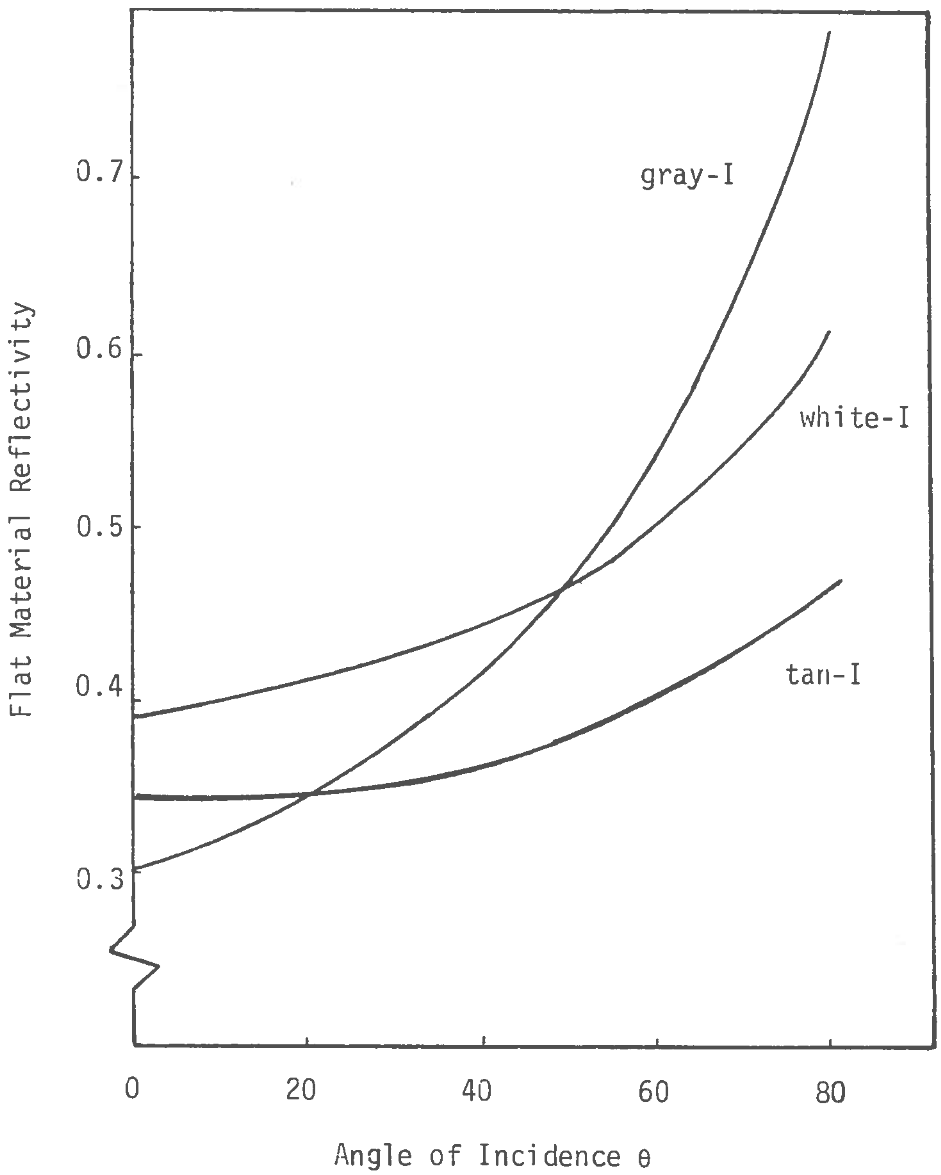


Figure 15. Reflectivities for Flat Materials

The relationship between the apparent absorptivity, transmissivity and reflectivity is

$$\alpha_a + \tau_a = 1 - \rho_a \; . \tag{13}$$

Having theoretically calculated the apparent reflectivity for the folded material as a whole, the apparent transmissivity and apparent absorptivity can be obtained from Equations (14) and (15).

$$\tau_a = \tau_{\Omega=0} \left(\frac{1 - \rho_a}{1 - \rho_{\Omega=0}}\right) \tag{14}$$

$$\alpha_a = 1 - \rho_a - \tau_a \tag{15}$$

Theoretical results obtained by this analysis have been checked and verified by experimental investigations in the University of Florida Solar Energy and Energy Conversion Laboratory with the University of Florida-ASHRAE solar calorimeter.

If two-dimensional grooving or folding configurations are used, resulting essentially in square block or stub systems, the apparent reflectivity can be expressed by

$$\rho_a = \left(\frac{\rho flat + \rho grooved}{2}\right)^2 \tag{16}$$

This theoretical analysis, as verified by experiment, shows that for a material with a flat material reflectivity of 0.5 the geometry as analyzed above produces an effective or apparent reflectivity of 0.18, and a flat material reflectivity of 0.1 results in an apparent reflectivity of 0.0064. For all practical purposes, the geometry or configuration is able to produce materials which will absorb all the energy which falls upon them.

Similar analyses, as presented above, have been made for sinusoidal configurations, V-notches resulting in pyramids in the two-dimensional arrangement, and others, but, in the interest of brevity, those analyses are not presented here.

The results obtained for these other configurations were essentially the same. All indicated the tremendous effect of geometry and the possibility of using proper configurations to produce almost totally absorbing surfaces.

3. Application of Antenna Theory

If the surfaces and configurations developed in the above analyses are used, electromagnetic radiation arriving at these "textured" surfaces, practically all the impinging energy can be absorbed.

Normally the absorbed energy will be converted into other forms and, in most cases, appear as heat which can then be guided and utilized by the sciences of heat transfer and thermodynamics, respectively.

If the geometric shapes are made to satisfy the requirements of antennae and antenna theory, they should convert the absorbed energy first into electricity. With proper coupling arrangements into these geometric shapes, it

should be possible to extract the absorbed energy in the form of electricity before it becomes heat, and at conversion efficiencies greatly in excess of those presently obtained with solid-state devices.

Antenna theory must obviously be modified when applied to power conversion since it requires a proper spacing of the individual elements in arrays, while a maximum power conversion requirement is that all the beam energy must be intercepted.

Figures 16, 17, and 18 present possible answers to the geometric configuration requirement, which can also serve as antennae. The shapes presented here are pyramids (sometimes truncated), cones and helixes. Other shapes are naturally possible.

For power conversion, many elements must be used and put together into an array covering large areas. The energy in solar radiation is approximately 1 KW/m^2.

The antennae designs can be arrived at as shown in Figure 19. Starting out with a simple dipole, the basic antenna element with its accompanying radiation pattern is usually thin and narrow and is shown in (19A). Since the solar spectrum includes frequencies with appreciable energy in the range from about 0.1 to about 3.0μm, the antenna element should be broadband. This can be accomplished by adding thickness to it or reducing the L/D ratio. For communication purposes, where antennae are widely used, they should only respond to one frequency and discriminate against the others. For solar power conversion the requirement is that it responds to all wavelengths. A possible configuration is shown in Figure 19B.

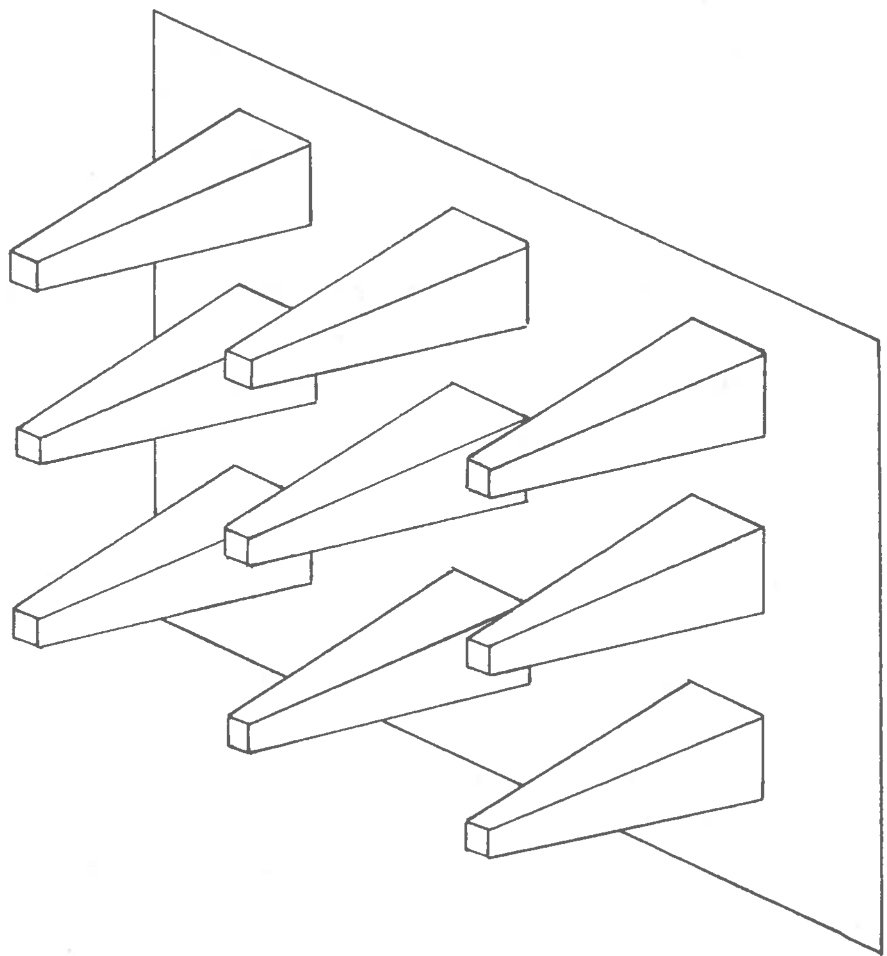


Figure 16. Truncated Pyramid Antenna
Array Configuration

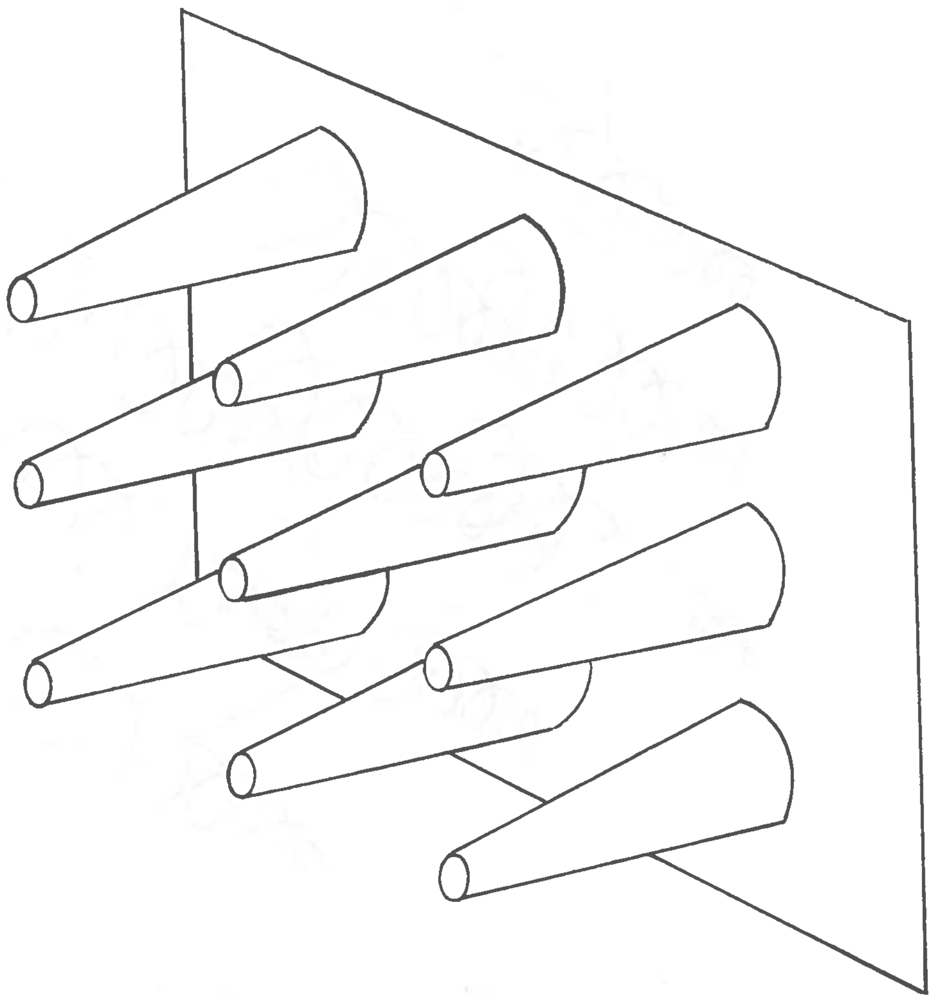


Figure 17. Truncated Cone Antenna Array Configuration

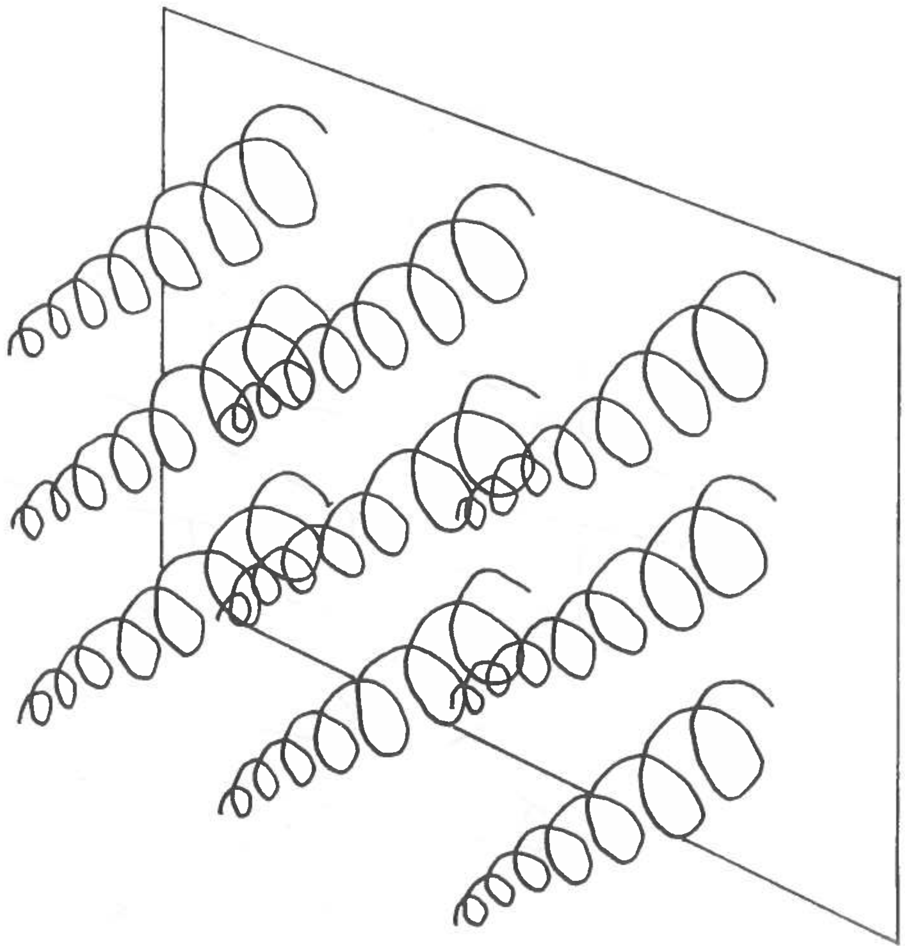


Figure 18. Conical Helix Antenna Array Development

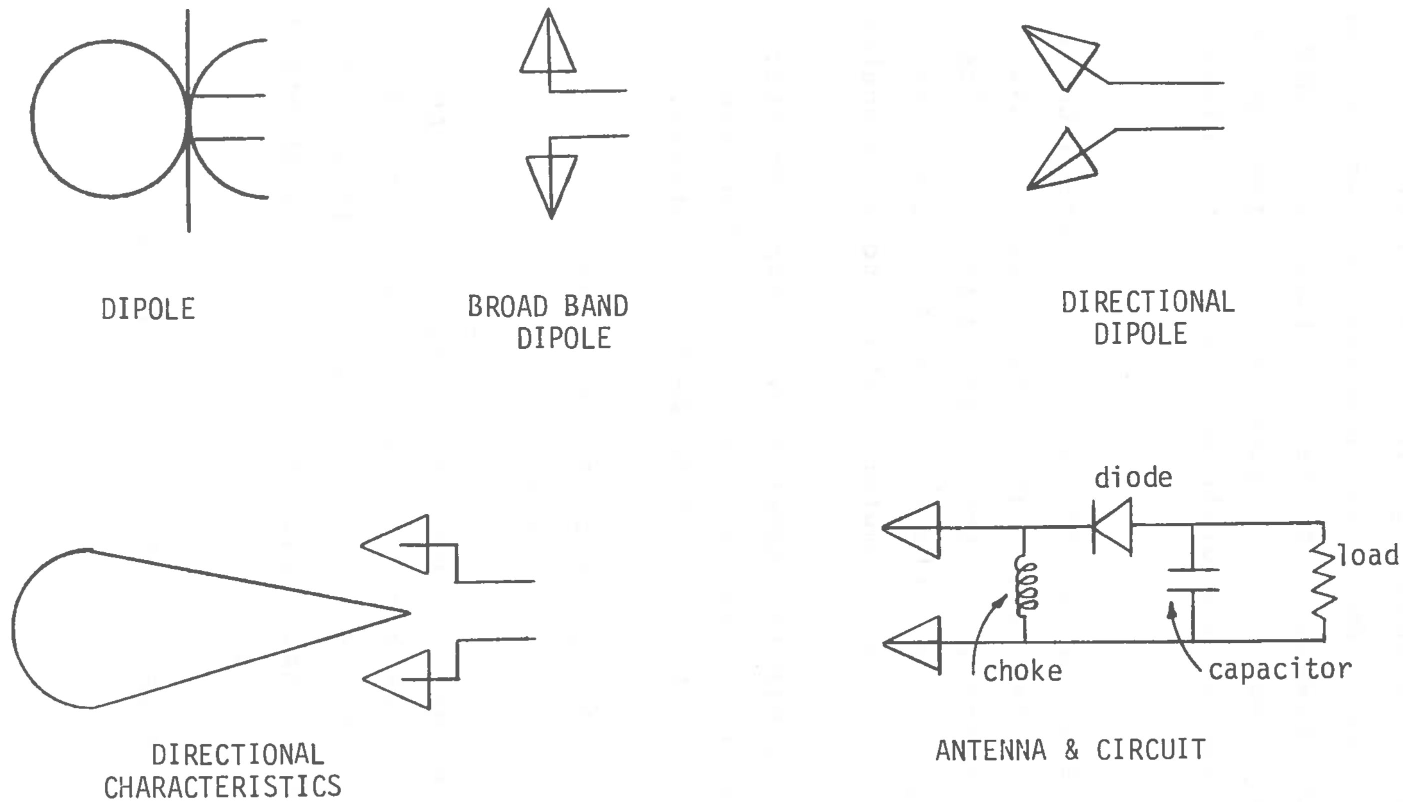


Figure 19. Power Conversion Antenna Array Development

To give the elements greater directional characteristics and allow closer spacing (a power conversion requirement), the elements can be bent forward as shown in Figure 19C, and, finally, in Figure 19D. In the latter figure, the change in lobe distribution from the dipole is also shown.

Since, very high AC frequencies are encountered (especially when solar energy is used) it may be advantageous to convert the energy to DC (even though there will be losses in this conversion), and attach a conventional electronic circuit, allowing DC loads (motors, etc.) to be operated.

The actual electromagnetic wave characteristics of the elements of different shape can be obtained from the electromagnetic wave theory, or Maxwell's equations.

Some equations and results pertinent to this investigation are presented here.

Most antennae for engineering application today are made from metals. However, nature uses dielectric materials in its conversion from solar energy to electricity. For this reason, the main emphasis will be on dielectric antennae in the treatment presented.

Maxwell's equation can be presented as

$$\mathrm{CURL}\ \tilde{E} = -\, i\omega\mu\, \tilde{H} \tag{17}$$

$$\begin{aligned} \mathrm{CURL}\ \tilde{H} &= i\omega\varepsilon\, \tilde{E} \\ \mathrm{DIV}\ \tilde{E} &= 0 \\ \mathrm{DIV}\ \tilde{H} &= 0\ . \end{aligned} \tag{18}$$

Equations (17) and (18) apply to charge-free media having zero conductivity.

Letting (definition)

$$\tilde{H} = \text{CURL } \tilde{A}^H \tag{19}$$

$$\tilde{E} = \text{CURL } \tilde{A}^E \tag{20}$$

where $\tilde{A}^H$ and $\tilde{A}^E$ are the magnetic vector potential and electric vector potential, respectively.

Assuming further that the vector potentials have only one component in the z or propagation direction, the field components are obtained

$$i\omega\varepsilon\, E_\rho = \frac{\partial^2 A_z{}^H}{\partial\rho\partial z}$$

$$i\omega\varepsilon\, E_\phi = \frac{1}{\rho}\frac{\partial^2 A_z{}^H}{\partial\phi\partial z}$$

$$i\omega\varepsilon\, E_z = \frac{\partial^2 A_z{}^H}{\partial z^2} + \omega^2 \mu\varepsilon\, A_z{}^H$$

$$H_\rho = \frac{1}{\rho}\frac{\partial A_z{}^H}{\partial\phi} \tag{21}$$

$$H_\phi = -\frac{\partial A_z^H}{\partial \rho}$$

$$H_z = 0 \qquad \text{(21 continued)}$$

$$E_\rho = \frac{1}{\rho}\frac{\partial A_z^E}{\partial \phi}$$

$$E_\phi = -\frac{\partial A_z^E}{\partial \rho}$$

$$E_z = 0$$

$$-i\omega\mu\, H_\rho = \frac{\partial^2 A_z^E}{\partial \rho \partial z}$$

$$-i\omega\mu\, H_\phi = \frac{1}{\rho}\frac{\partial^2 A_z^E}{\partial \phi \partial z}$$

$$-i\omega\mu\, H_z = \frac{\partial^2 A_z^E}{\partial z^2} + \omega^2 \mu\varepsilon\, A_z^E \qquad (22)$$

These equations can be applied to different systems such as circularly symmetric field distributions, noncircularly symmetric waves, etc.

Also obtained can be the general characteristic equation for electromagnetic waves in dielectric cylinders

$$\left[\frac{\mu_1 \; J_n' \; (x_1)}{x_1 \; J_n \; (x_1)} - \frac{\mu_2 \; H_n' \; (x_2)}{x_2 \; H_n \; (x_2)}\right] \times$$

$$\left[\frac{\varepsilon_1 \; J_n' \; (x_1)}{x_1 \; J_n \; (x_1)} - \frac{\varepsilon_2 \; H_n' \; (x_2)}{x_2 \; H_n \; (x_2)}\right] =$$

$$- \frac{n^2 \gamma^2}{\omega^2} \left(\frac{x_2{}^2 - x_1{}^2}{x_1{}^2 x_2{}^2}\right)^2 \qquad (23)$$

While these analyses only consider one wavelength at a time, the basic characteristics obtained form an interesting foundation for the actual problem at hand.

Much work has been done with metallic configurations on both transmitting and receiving antennae. Considerably less work has been done with dielectric materials, but Kiely used dielectric rods (Figure 20), remarkably similar to nature's design of insect antennae (compare Figures 20 and 5). He reported results for single-rod antennae of different lengths (Figure 21), presenting them in terms of polar diagrams.

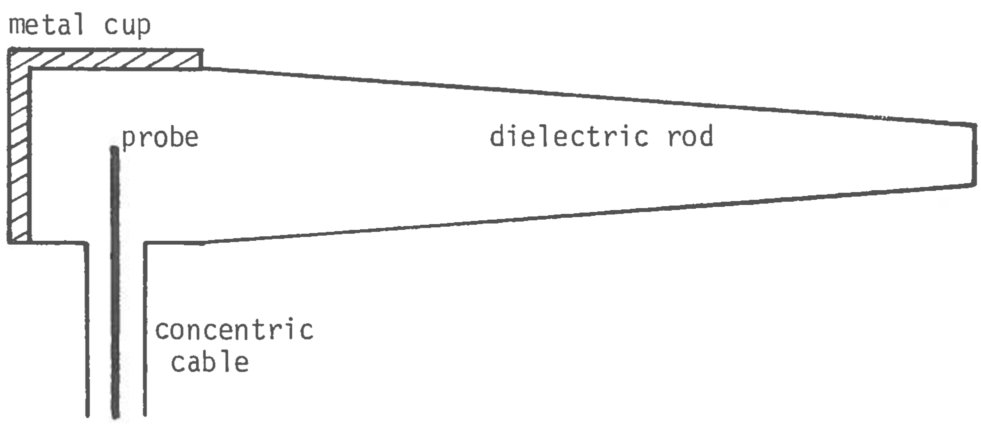


Figure 20. Dielectric Rod Aerial, Probe Method of Excitation

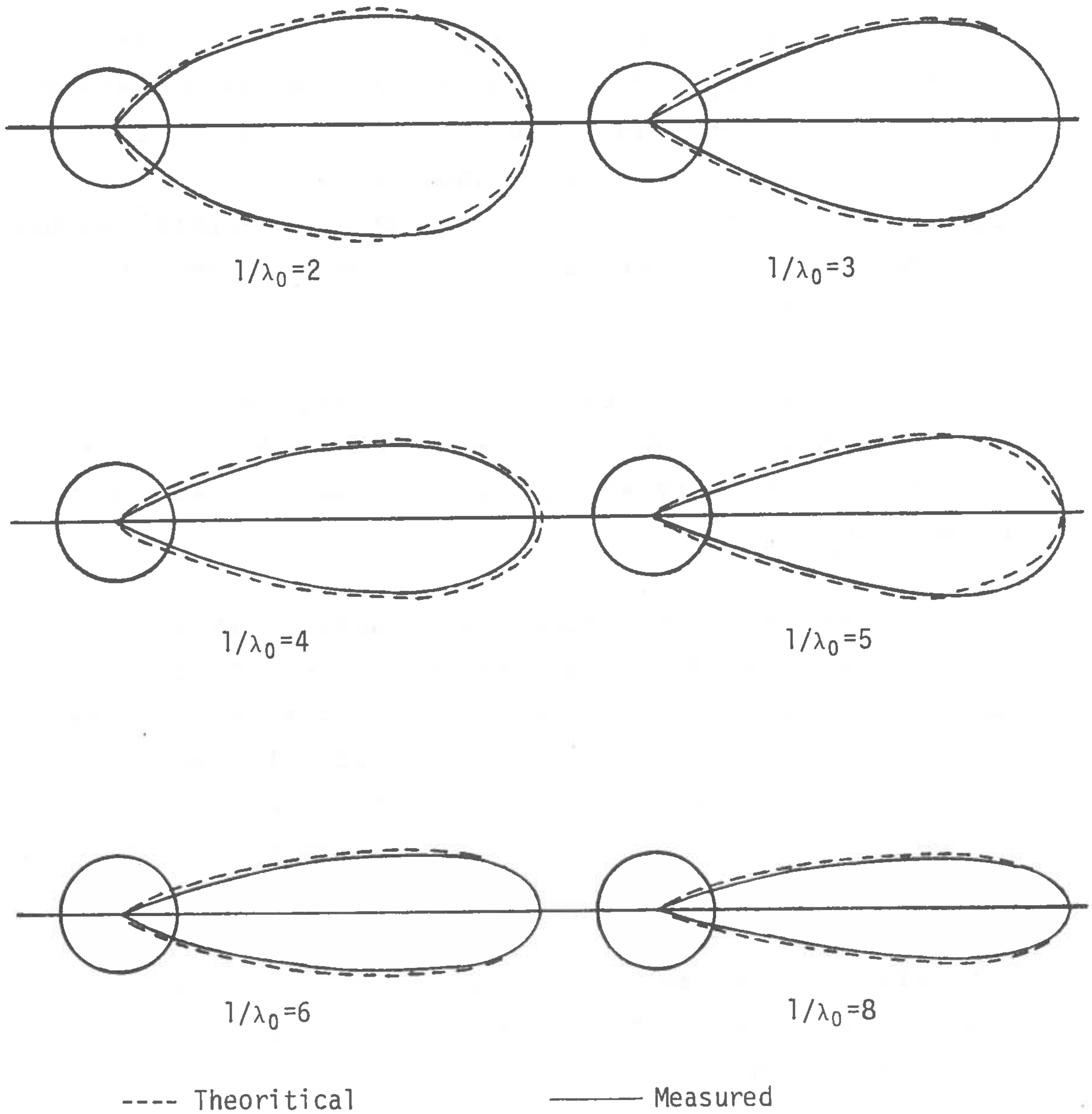


Figure 21. Polar Diagrams of Tapered Rods

Figure 22 gives similar information for a two-rod array, and Figure 23 presents a polar diagram for a four-rod array. All these plots compare theoretical and actual measured values, presenting them on a relative basis.

Figure 24 presents experimental data on the polar diagram for a tapered rod when the frequency is varied. If tubes are used instead of tapered solid rods, their performance as a function of wall thickness is given in Figure 25, again comparing theoretical with experimental values. Figure 26 gives the results for different tube lengths on the radiation pattern.

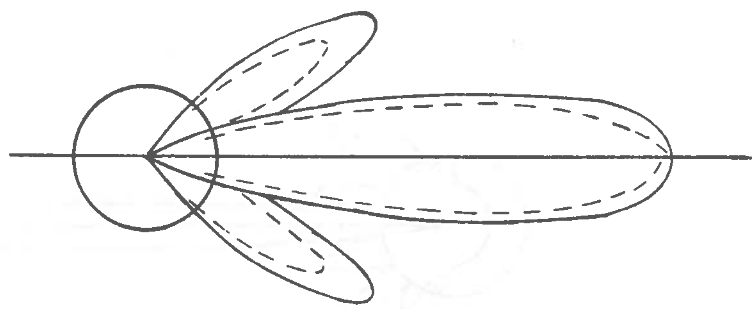
The above presentation shows that much work has been done on single-element antennae and considerably less on arrays. Practically all the work focused on single-frequency response.

When many frequencies are involved at the same time (this is mentioned but not treated) some interactions make analysis on the basis of antenna theory very complicated and difficult. However, experimental evaluation and development with theoretical guidance may be a quicker approach to obtaining the true characteristics of particular arrays.

Comparisons may be needed to combine antenna theory with the maximum absorption requirements. This was presented theoretically, using the solar energy radiation characteristics.

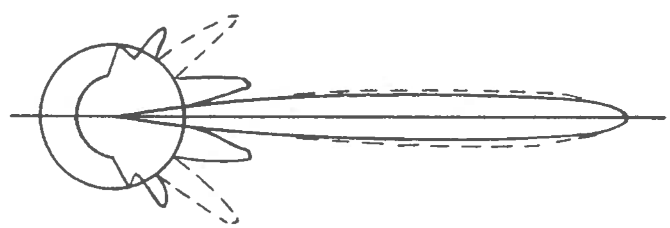
The frequency interaction may be advantageous, increasing the conversion efficiency, but may give some problems through wave interference.

Nothing in the theories would indicate that very high power conversion efficiencies are not possible.



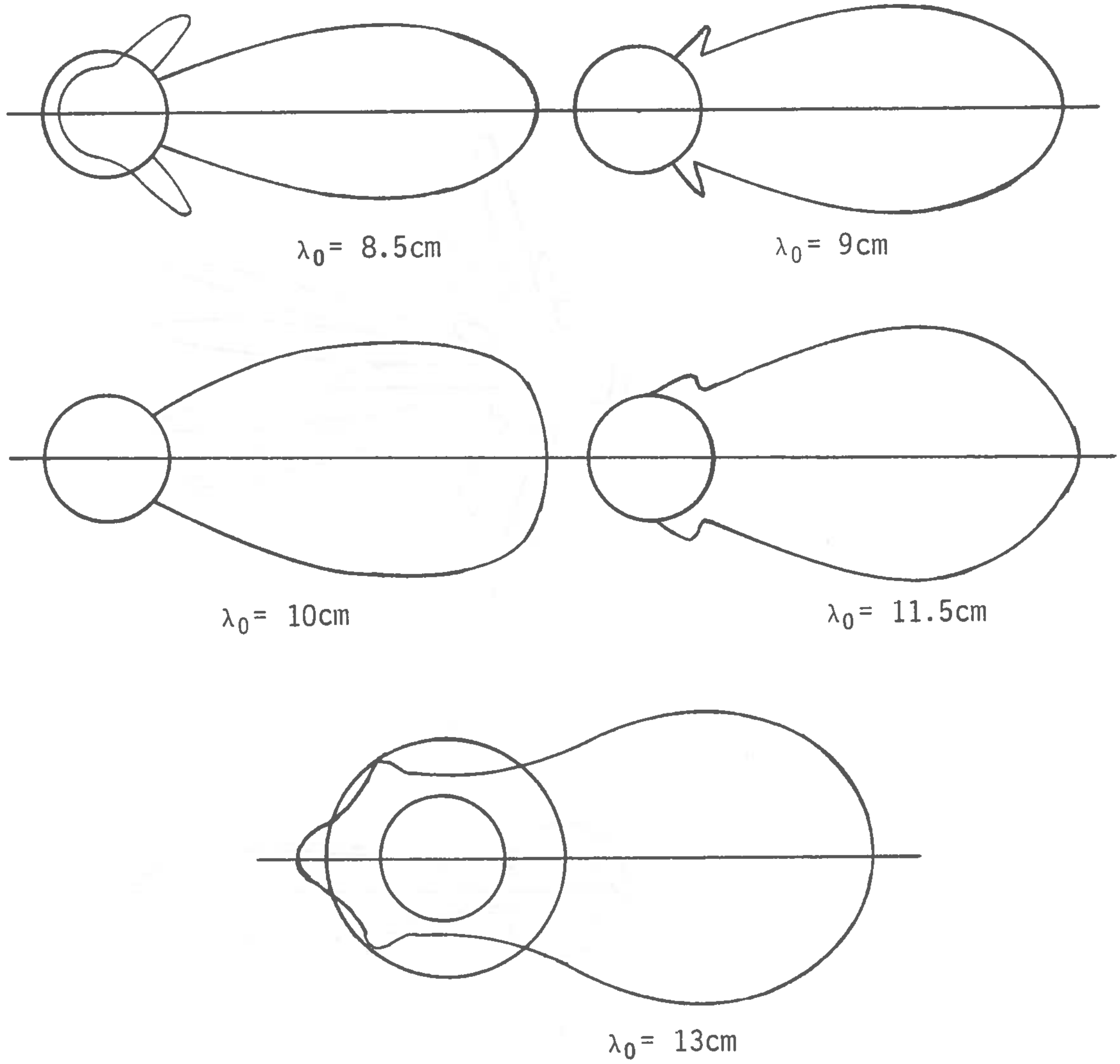
---- Theoretical —— Measured

Figure 22. Polar Diagram of Two Rod Array



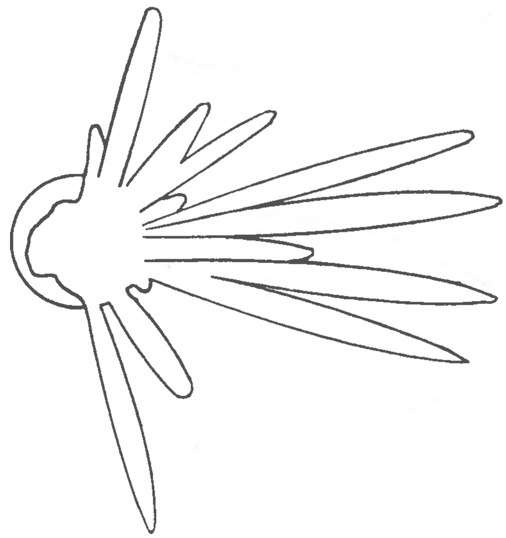
---- Theoretical —— Measured

Figure 23. Polar Diagram Four Rod Array

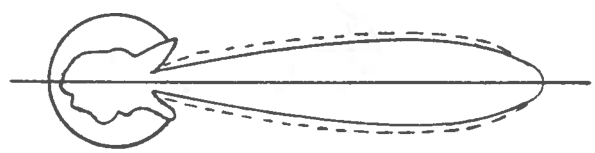


$l/\lambda_0=2$ and $d/\lambda_0=0.46$ at $\lambda_0=10$cm

Figure 24. Measured Polar Diagram Tapered Rod and Different Wavelengths



$t/\lambda_0 = .126$



$t/\lambda_0 = .03$

---- Theoretical —— Experimental

Figure 25. Effect of Tube Wall Thickness on the Radiation Pattern

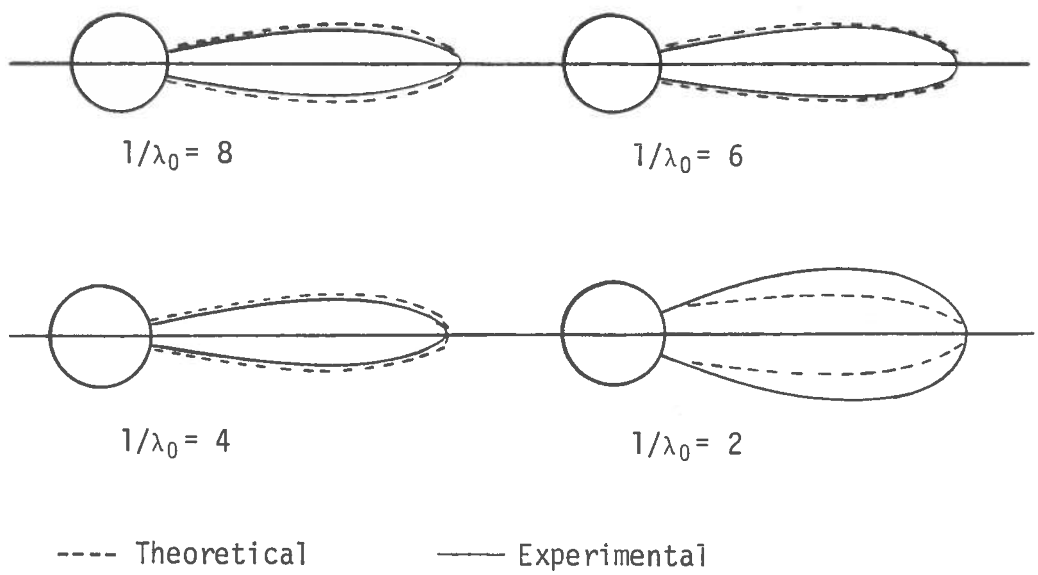


Figure 26. Effect of Tube Length on the Radiation Pattern

SECTION III

EXPERIMENTAL VERIFICATION

Having worked out the theory and having, therefore, an indication that high conversion efficiencies from solar energy to electricity are indeed predicted, it is necessary to verify and prove the predictions through experimental work.

The experimental procedures and plans were made so as to have a logical sequence of experimentation, and at the same time, the maximum probability for success.

The experimentation was guided by the availability of equipment, which, when used, could greatly reduce the cost of the present investigation.

A. APPROACH

Based upon the theory and the analysis of the problem of converting solar energy or electromagnetic waves to electricity, the geometry is of utmost importance. Both absorption characteristics and antenna theory must be considered.

The materials chosen are very important. In antenna communication technology (not in power conversion), metallic elements are used, while nature uses dialectrics.

The conversion efficiency, the ultimate goal to achieve as high a value as possible, must be determined. This can be accomplished through direct measurements and an analysis of the losses. Understanding the reasons for the losses allows us to reduce them.

Such things as center frequency, bandwidth, and beam width will eventually be determined for single elements as well as for combinations.

The final design, as predicted from theory and dictated by common sense, must be a closely spaced array. This will intercept all the energy in a beam, absorb it and convert it to electricity.

Because the geometry is of utmost importance, it was decided to start the experimentation in the microwave range of frequencies. In this manner it is possible to shape the elements exactly to specifications and then, when these shapes are optimized, they can be miniaturized. Because the wave-to-surface interaction is not a function of size, the microwave investigation should give a good model for prediction and design for shorter frequencies.

Based upon the equipment available, it was decided to start in the range of 0.2 to 3.0 GHz, then go to about 10 GHz, jump of one to two orders of magnitude to 100 GHz and finally, to solar and light frequencies.

1. Microwave Equipment and Instrumentation

Since resources were limited, to reduce the cost of this investigation as much as possible, it was decided to utilize available equipment.

a. 0.2 - 3.0 GHz

(1) Equipment

. A Power Signal Source, Type 125, from AIL, (A Division of Cuttler-Hammer, Deer Park, Long Island, N.Y.

11729), covering a range from 0.2 to 3.0 GHz was found, repaired and used for this investigation.

A 8551 A Spectrum Analyzer - RF Section, Hewlett-Packard, with a 851 A Spectrum Analyzer-Display Section, was also found and could be put in operating condition. It covered a range from 10.1 MC to 40 GHz.

Thus, two units constituted the generating equipment and the analyzing equipment.

To measure the power output of the receiving device, a General Microwave, Model 454 A, Thermoelectric Power Meter, covering a range from 0.3 W to 100 mW was used, but reconstituted (full-scale) was obtained. A Power Head, N 421 D, Serial number 143057 was also obtained from General Microwave.

A Power Density Meter, Model NF-157 Serial number 36, Empire Devices Products Corp., Amsterdam, N.Y., covering a range from 200 MC to 10,000 MC, used, and reconstituted was also obtained and used to measure the power beam intensity.

In addition to the above, standard laboratory equipment, multimeters, thermometers, small motors (DC) and high-frequency diodes were used.

(2) Receiving Element Design and Manufacture

To check on the antenna theory and predicted performance, two dipoles of larger than normal diameter (to give them more broadband characteristics) were designed and built for testing against the presently accepted theories. However, broadband antennae of various degrees of directivity are needed for this effort.

Figure 27 shows some of the antennae. In front is one of the dipoles. On the right is a tuneable cone (excited at the estimated maximum current point), an inverted cone receiver, a tuneable pyramid and a conical helix. These are all single element receivers. On the left is a two-by-two array, and in the center a four-by-four array of the pyramids. Each single element of the absorber system is tuneable.

All antennae elements and arrays shown in the figure are made of copper with plexiglass insulators and copper reflector plates. Other materials were used, as mentioned earlier in the discussion. Figure 28 shows a two-element array of dielectric material; a wooden base with gypsum-truncated cones forming the active elements. The dielectric elements are excited by metallic probes forming the end of the transmission line.

For most experimentation, the above elements were used to receive and convert the microwave beam to electricity.

Figure 29 shows the complete experimental arrangement used to demonstrate the feasibility of the conversion of electromagnetic waves to electricity at conversion efficiencies in excess of 60 percent. The figure shows the microwave generator (lower right unit) generating microwaves in the range of 0.2 to 3.0 GHz. On the right is the metallic two-element transmitting antenna. On the bottom is the dielectric two-element receiving antennae. The received signal is split and part of it is fed to the spectrum analyzer with display unit (far left). The other part is rectified by a diode bridge circuit (Figure 30). The rectified power is then used to drive a small DC motor shown in Figure 29, next to the transmitting antenna.

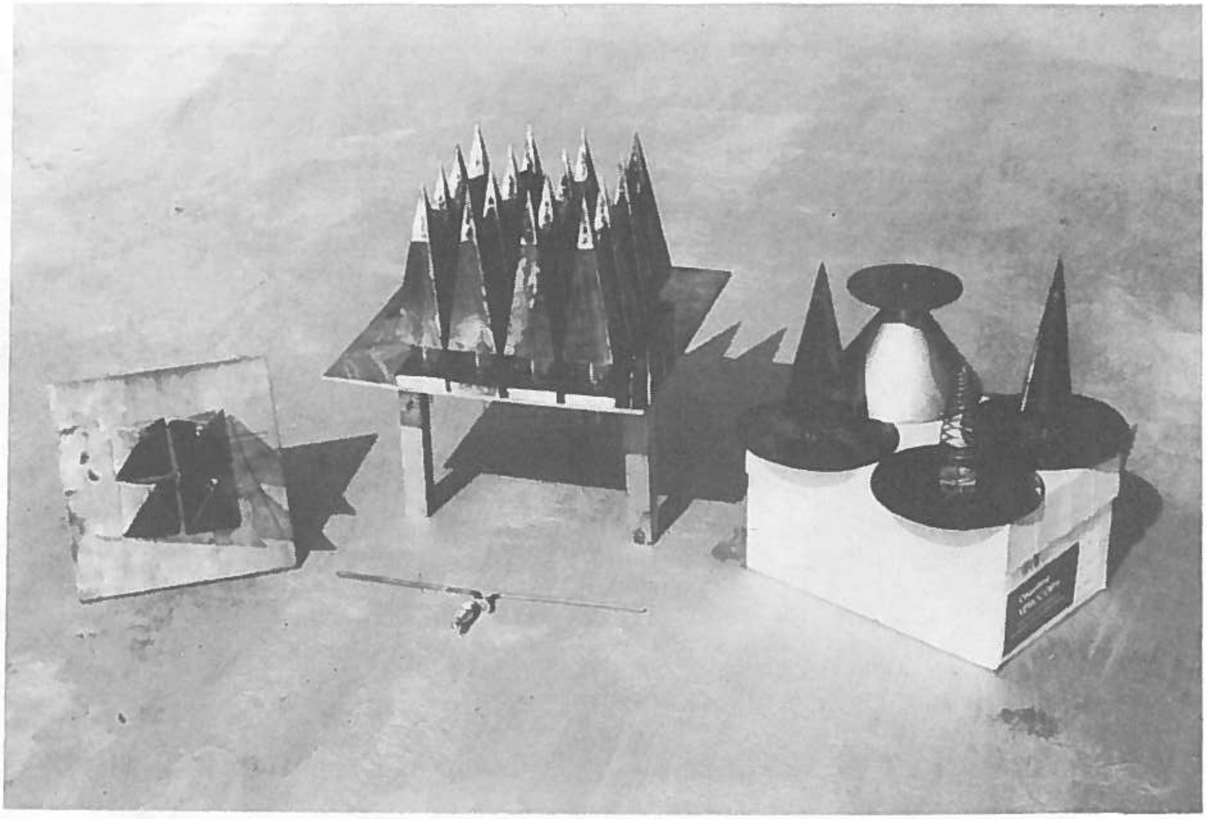


Figure 27. Receiving Antennae and Power Converters.... Dipole, Pyramid, Inverted Cone, Cone, Conical Helix in Single Elements 2x2 and 4x4 Power Converter Arrays for 0.2 - 3.0 GHz

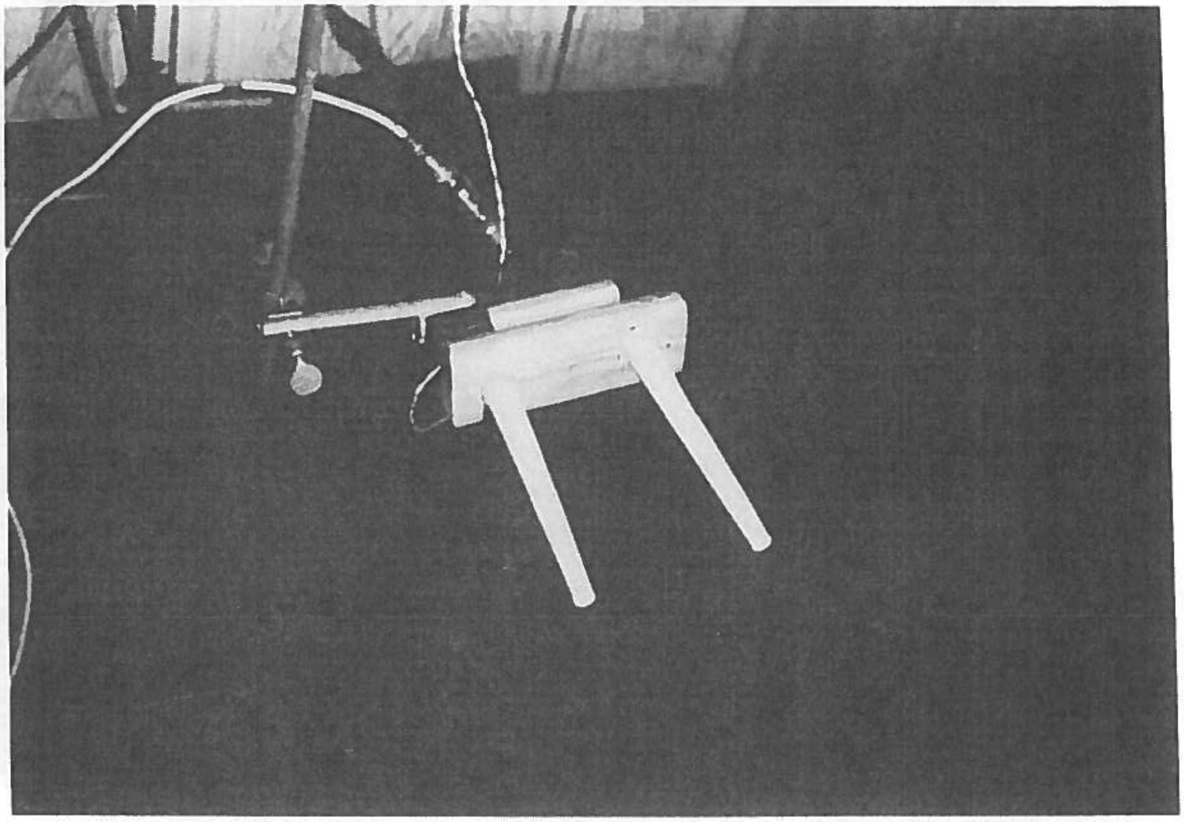


Figure 28. Two-Element Dielectric Power Converter... Truncated Gypsum Cones, Wood Base, Metallic Probe Exciter, and Metallic Transmission Line for 0.2 ~ 3.0 GHz

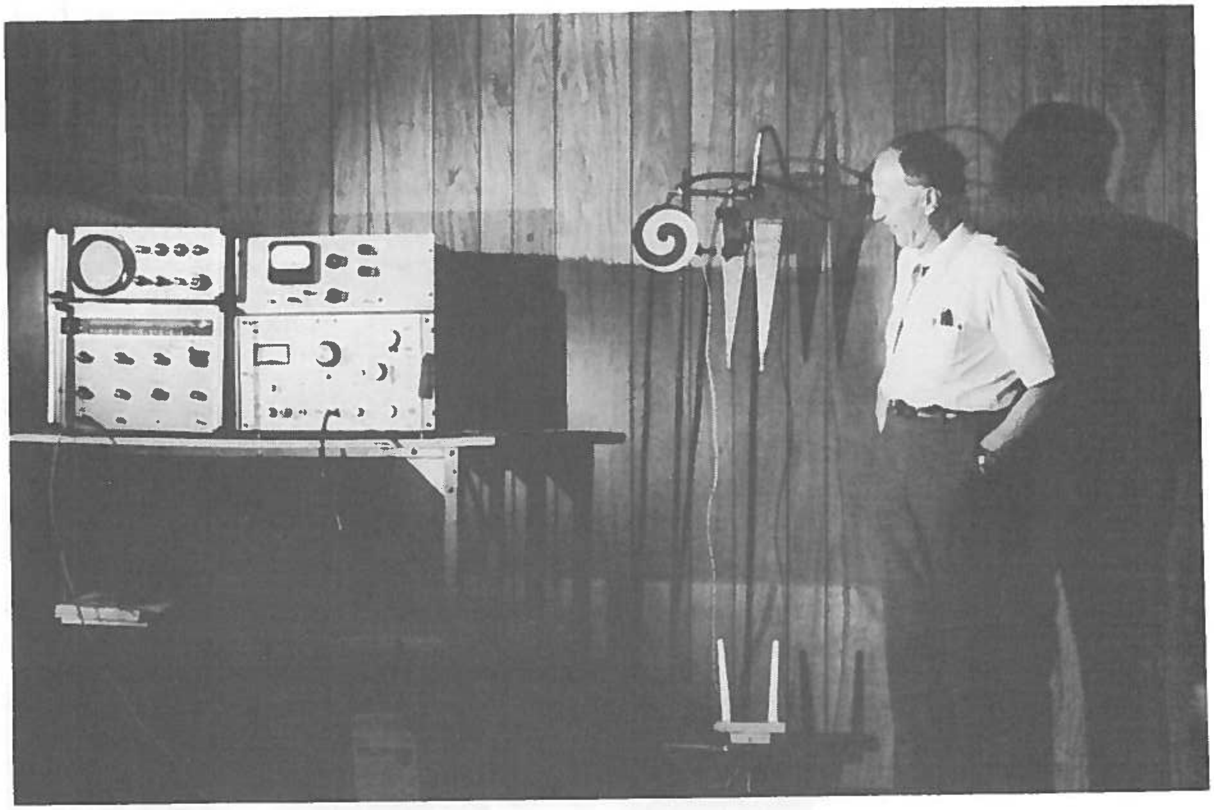


Figure 29. Experimental Power Converter Test Arrangement for 0.2 and 3.0 GHz.
Microwave Power Generator, Spectrum Analyzer and Display, Two-Element Metallic Transmitting Antenna, Two-Element Dielectric Receiving Antenna, Signal Splitter, Full-Wave Rectifier Bridge, and DC Motor

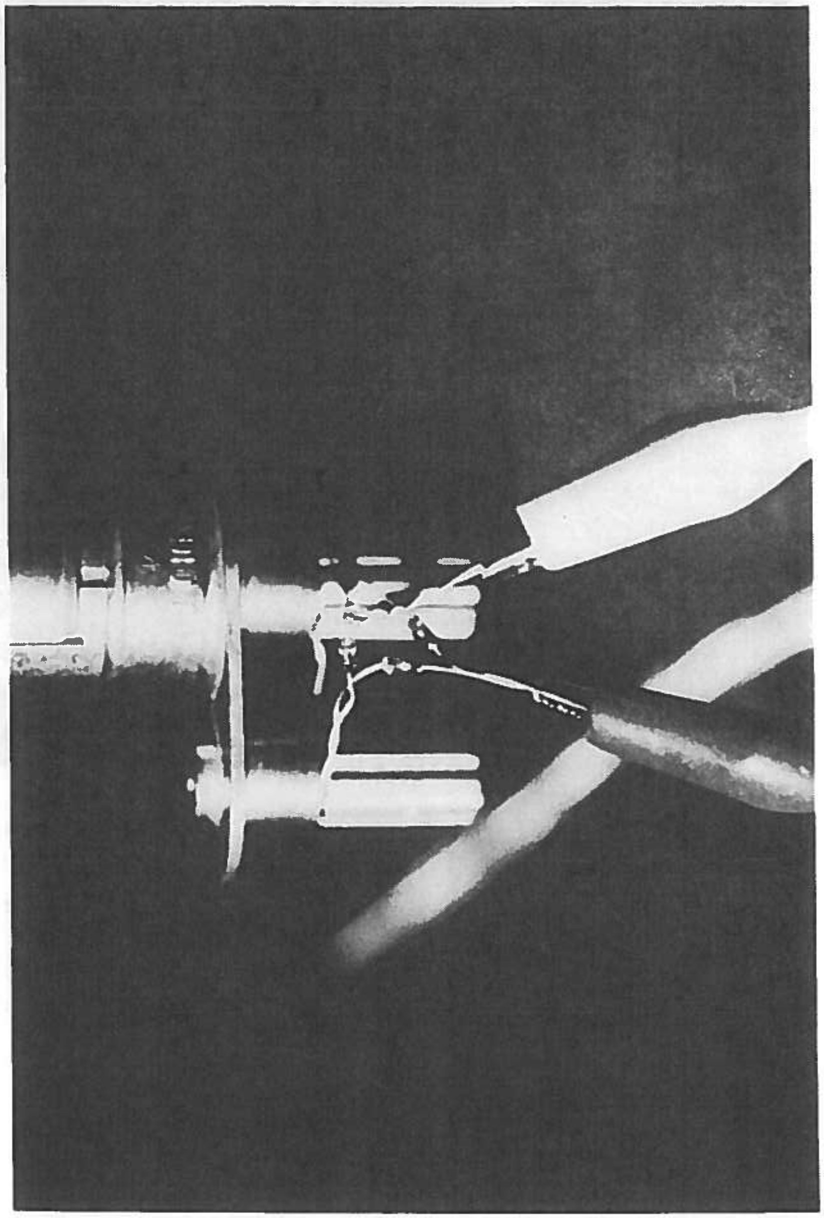


Figure 30. Diode Rectifier Bridge...
Microwave to DC
0.2 - 3.0 GHz

The received signal as delivered by the power antenna-converter is shown in Figure 31.

The various receiver-converters shown in the previous figures can be used in this arrangement, their conversion efficiency measured at different frequencies and angle of approaching beam.

While for solar conversion the converter must work at many frequencies at the same time, available equipment only allowed analysis at one frequency at any one time.

The spectrum analyzer measures the power output of the converter as with purely resistive load. However, the motor represents a true impedance load and demonstrates actual operating conditions.

b. 10 GHz

(1) Equipment

For the experimentation in this range the energy source consisted of a 10 GHz Gunn Diode Generator with Resonator, cavity, waveguide and horn.

For measuring the beam's intensity and its modification during the experimentation, a 10 GHz Diode Detector with Horn and receiver cavity, and a microammeter for the Signal Strength Readout were used.

Additional equipment such as waveguides, filters, and screens were used, as needed.

In the experiments, where the converted energy was coupled out of the waveguide with probes, the

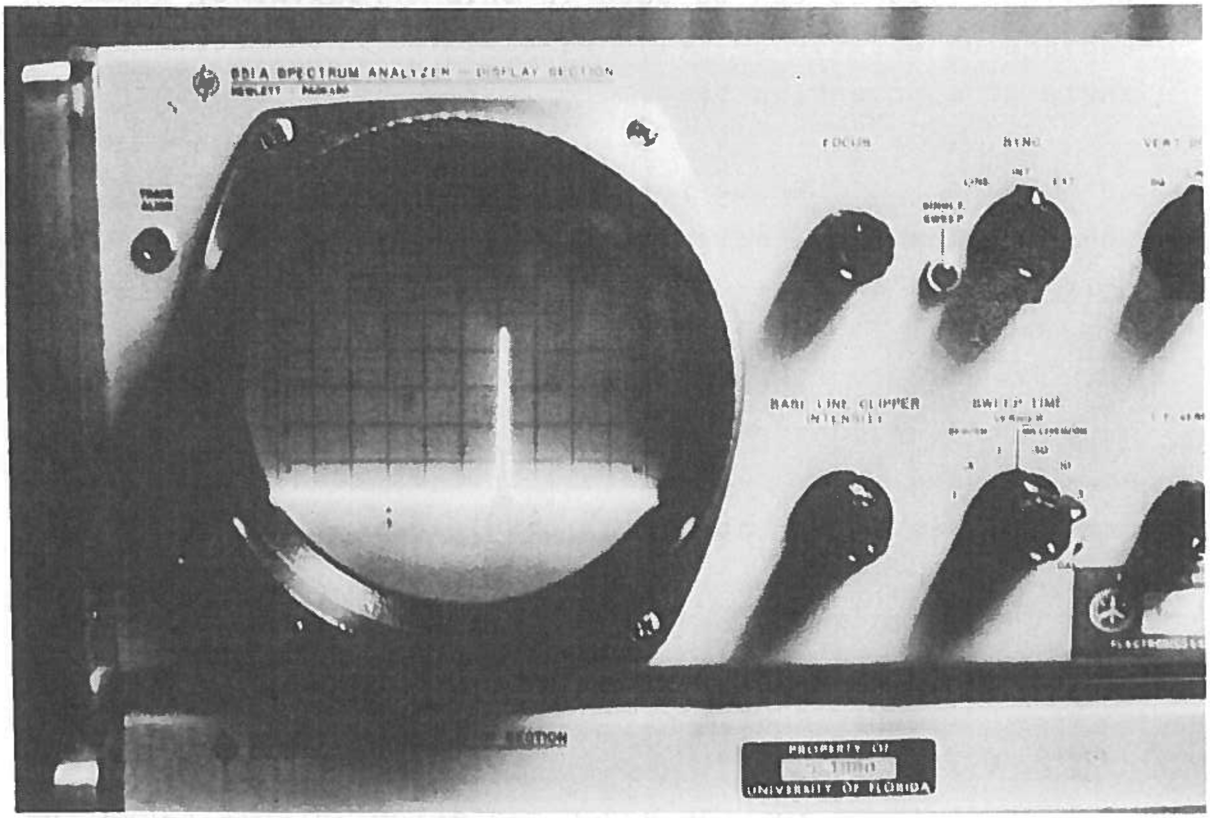


Figure 31. Spectrum Analyzer Displaying Receiver-Converter Power Output

resultant voltages or currents were measured with Keithly 600 Electrometers.

The typical experimental arrangement for the 10 GHz work can be seen in Figure 32.

(2) Receiving Element Design and Manufacture

A great number of antenna elements were needed to build upon the work carried out in the 0.2 to 3.0 GHz range and further optimize the receiver configurations a great number of antennae elements had to be made.

Since the frequency for this range of experimentation was fixed the elements had to be varied for the determination of design changes. In the previous, lower Microwave range the frequency could be changed, thus, the same element could be evaluated for response and performance.

In the 10 GHz range, the antenna elements and arrays made from dielectric materials performed better than the metallic ones. For this reason, most of the elements used in the experiments were made from wax coated paper.

Figures 33, 34, and 35 present some of the elements designed, manufactured and used. Their configurations are conical, cylindrical, and pyramidal.

c. 100 GHz

(1) Equipment

The equipment was borrowed from the Electrical Engineering Department of the University of Florida. It was fortunate that this equipment was available since its

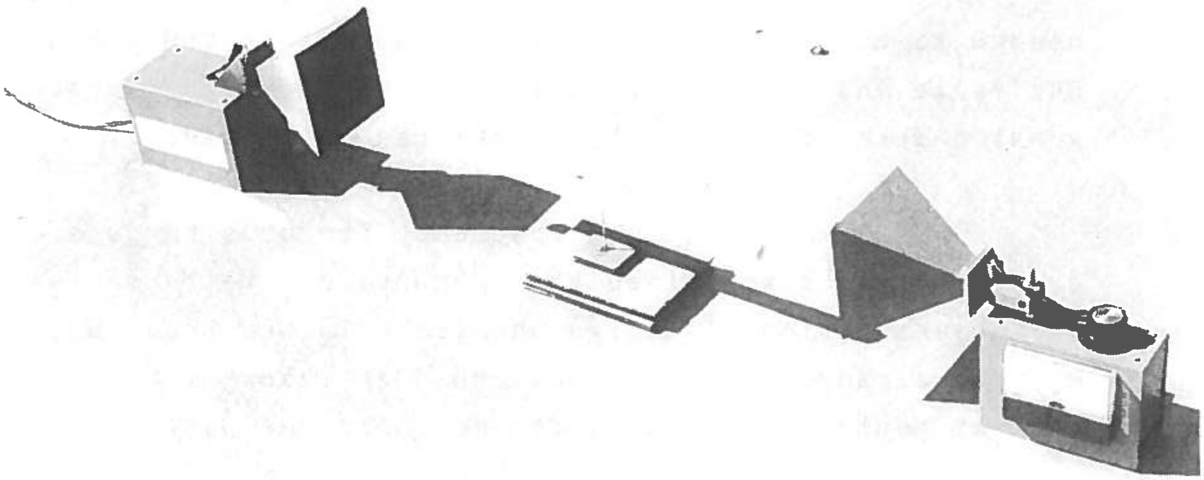


Figure 32. Truncated Cone Power Converter Test Configuration 10 GHz

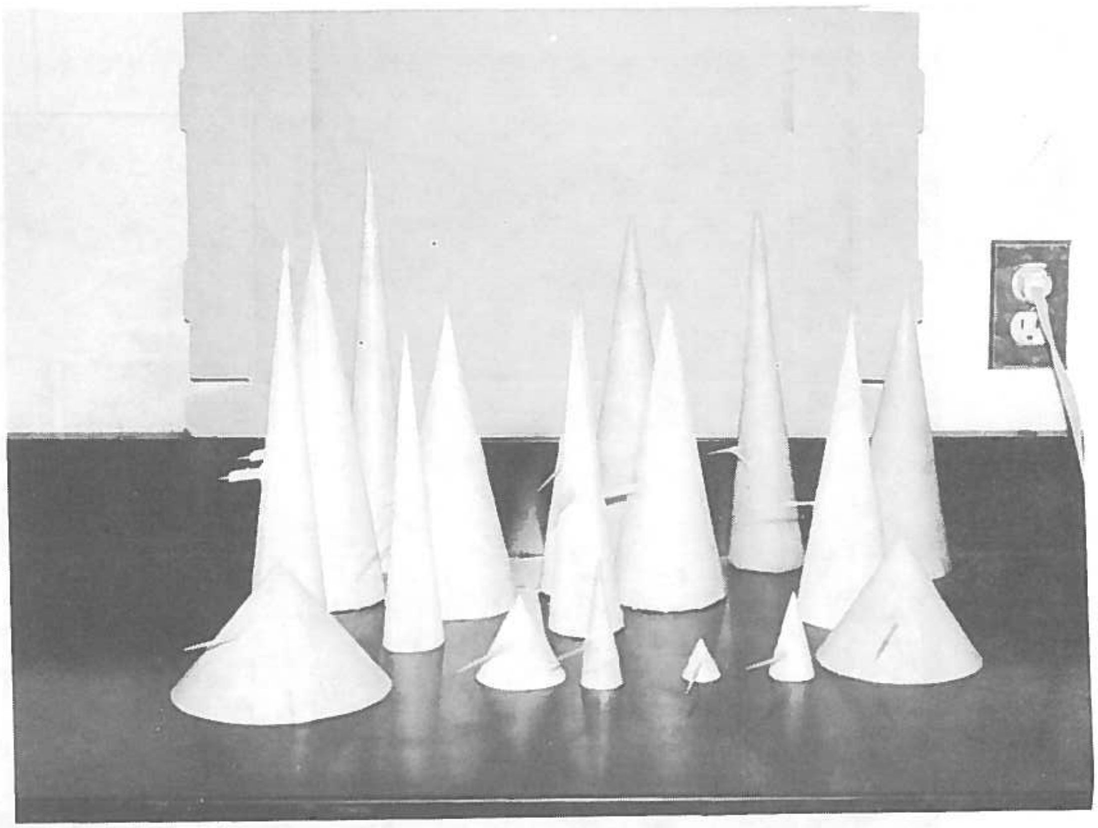


Figure 33. Conical Antennae Elements 10 GHz Range

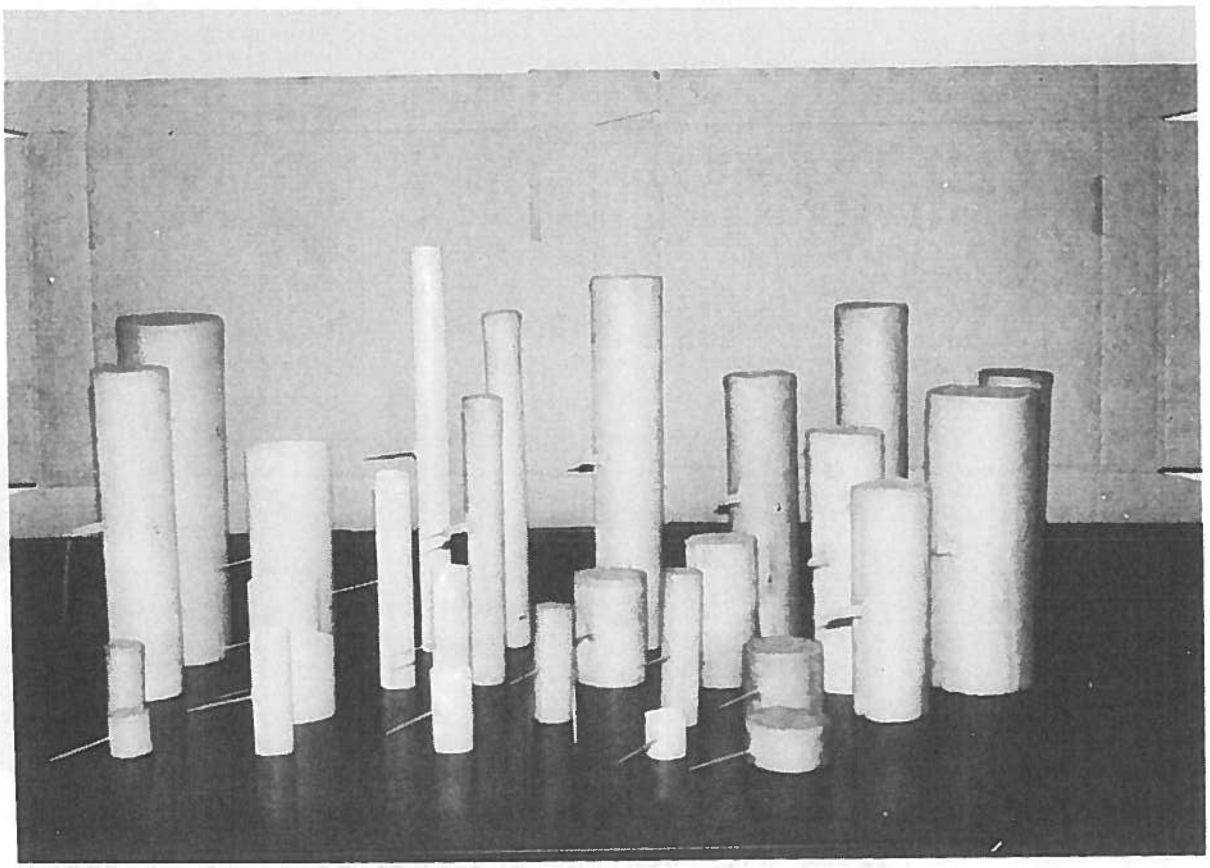


Figure 34. Cylindrical Antennae Elements 10 GHz Range

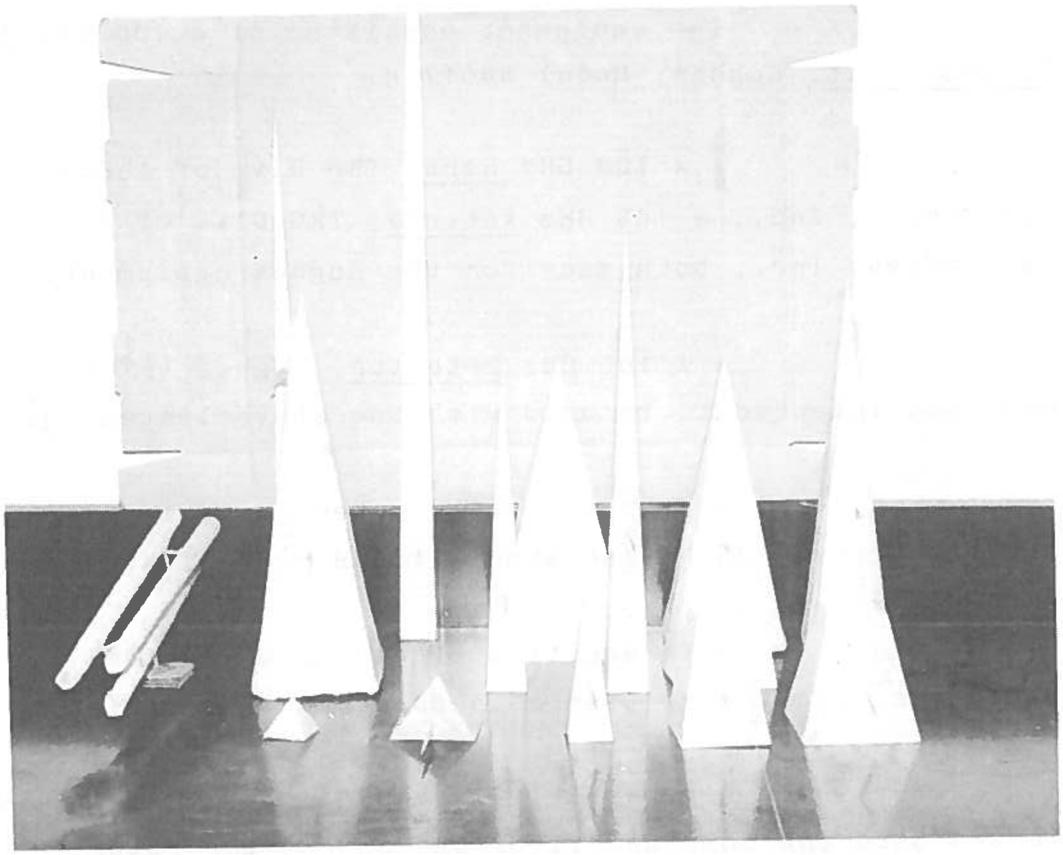


Figure 35. Pyramical Antennae Elements 10 GHz Range

cost is close to $250,000. The privilege of using this equipment saved a tremendous amount of money and allowed the miniaturization by another order of magnitude.

The equipment consisted of a 100 GHz Sweep Control Unit, Hughes, Model 44017 H.

- A 100 GHz Horn, TRG Div. of ALPHA Industries, Inc., a 100 GHz Antenna, TRG Div. of ALPHA Industries, Inc., both made for the Hughes equipment.

- A 100 GHz Detector, Hughes 45776 H, also made and intended to be used with the above listed equipment.

- A HP 432 Power Meter, used in conjunction with Coupler 45326 H/ Isolator 45116 H - 1000, Hughes.

- In addition pieces of waveguides, splitters, etc., were used as needed.

Figures 36, 37, and 38 show the equipment as it was used and some detail of the source generator.

(2) Receiving Element Design and Manufacture

The antenna elements were designed and manufactured identically to the ones for the 10 GHz work, except that they were scaled down by a ratio of 1/10 corresponding to a wavelength of 3 mm.

The elements were carefully made of paper and coated (by dipping) with wax. Very small discs and three-pronged probes were made, allowing the energy to be coupled out from the wave-guides. Multiple element arrays were used in the evaluation.

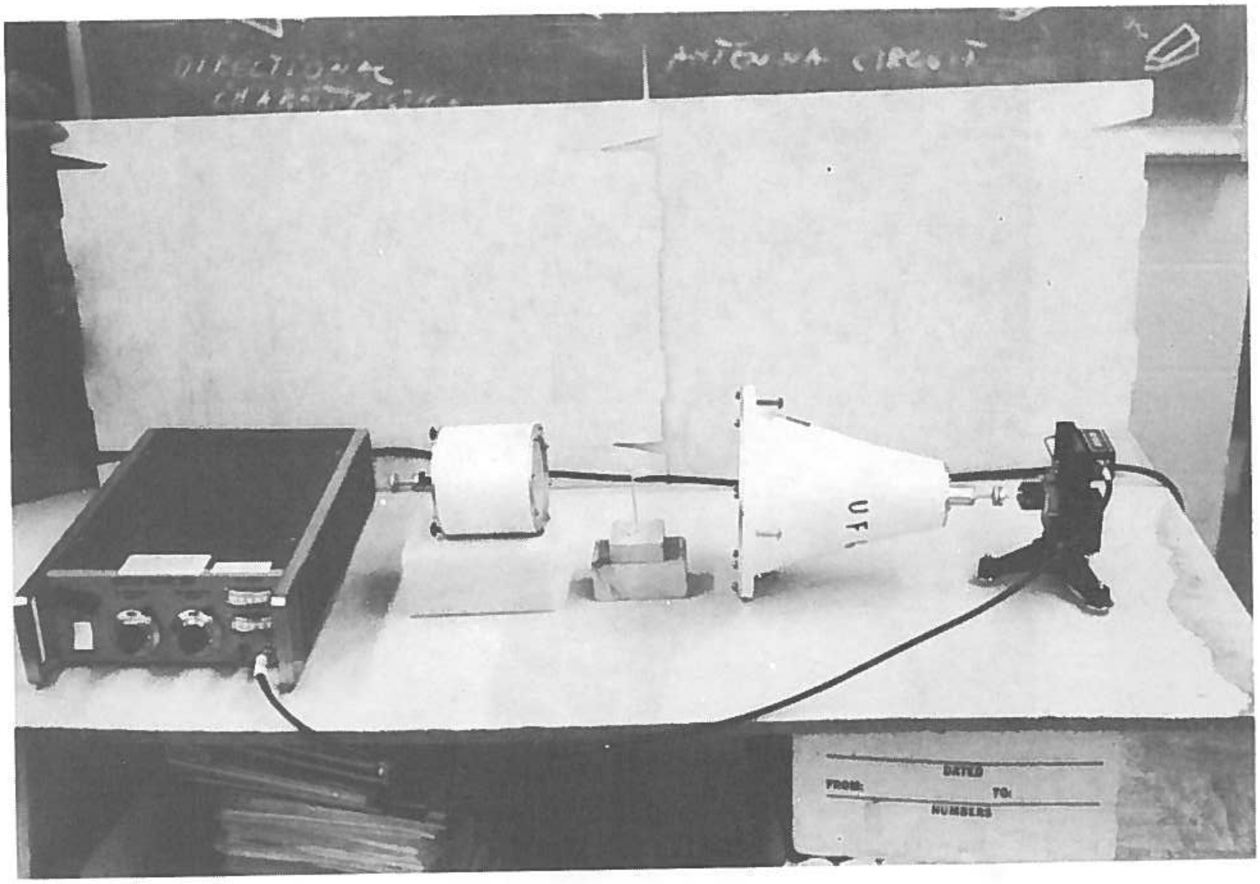


Figure 36. 100 GHz Experimental Equipment
Sweeper Control, Generator With Horn, Cavity
Detector, Four Element Converter

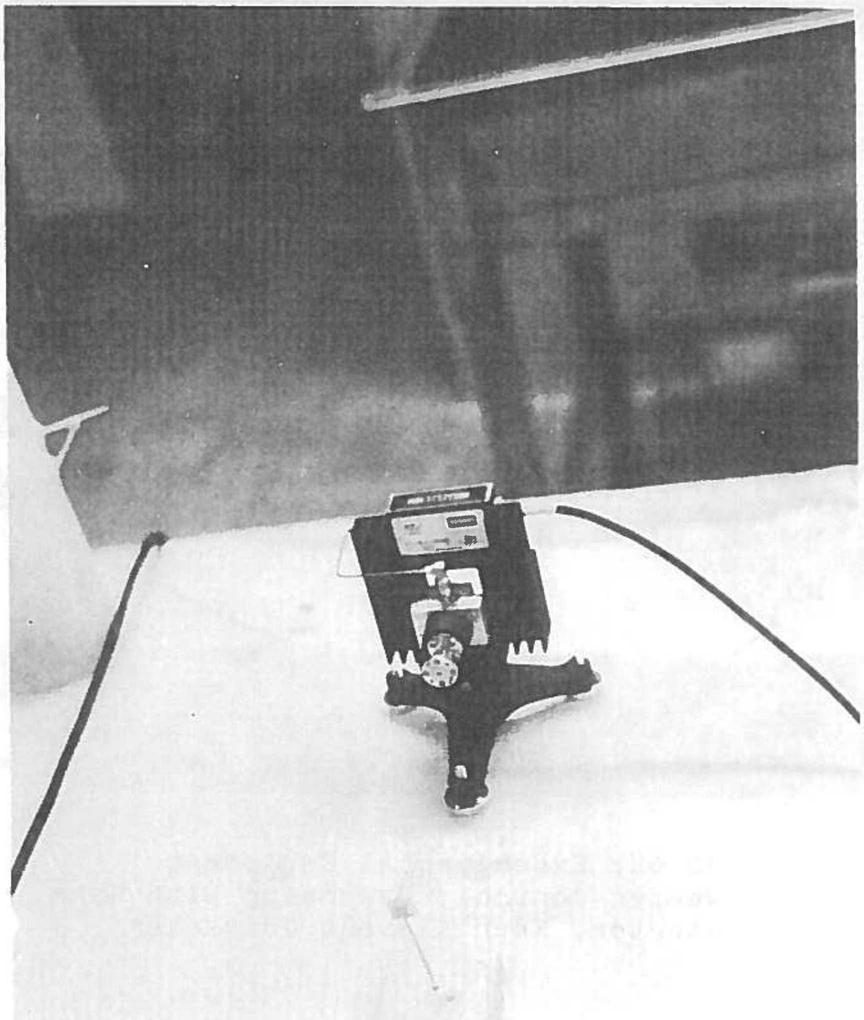


Figure 37. 100 GHz Source Generator
Without Horn

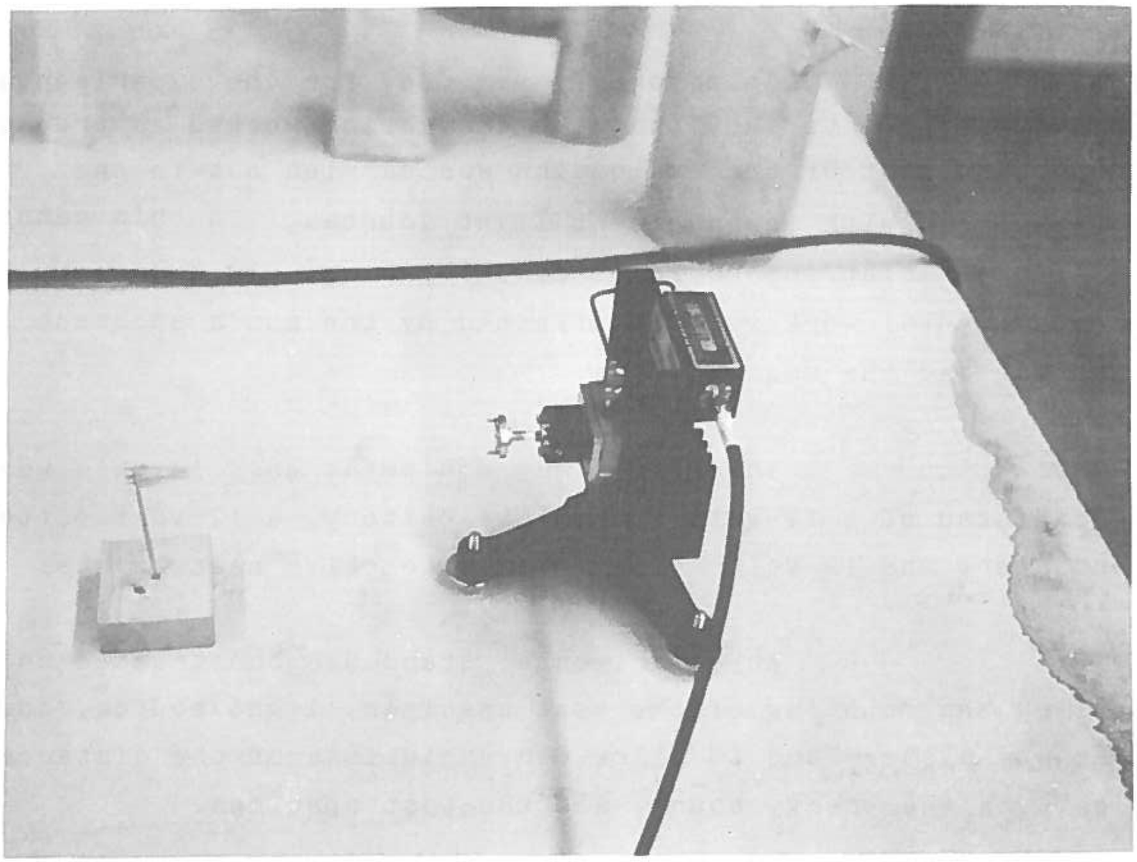


Figure 38. Side View 100 GHz Source Generator with Four-Element Converter

d. Solar/Light Range

(1) Equipment

Solar energy was used for the experimentation in this range to show that the conversion worked as predicted but then most of the evaluation was carried out in the laboratory with incandescent light sources. In this manner, all the variations could be controlled or held constant. The experimental work was not affected by the sun's apparent motion and the weather.

The laboratory equipment used in this work consisted of a 12-volt automotive battery, a 12-volt battery charger, and 12-volt sealed beam automotive head lights.

An experimental stand was constructed to allow the mounting of the test specimen, light source, and sensor system, and to allow for variations of the distance between the energy source and the test specimen.

The Keithly 600 Electrometer was again used to evaluate the output from the converter.

An optical microscope was used to evaluate and analyze the geometric configurations of the antenna arrays used in these experiments.

(2) Receiving Element Design and Manufacture

Although all the processes necessary to design and manufacture the perfect array, have been used, for other purposes, it was decided in the interest of time and cost to use less perfect but existing systems.

Since the work at microwave frequencies indicates that the pyramid seems to be the best configuration, Silicon carbide crystals fit the requirements for test purposes. They are grown then crushed and used in Carborundum paper, which serve as test samples. They come in many sizes, and are inexpensive. Numerous grades of Carborundum papers were obtained, prepared and used to evaluate the many parameters.

Figures 39 and 40 present the Solar/Light to Electricity converter under test. Figures 41, 42, and 43 present the different Carborundum® paper samples and samples with their respective sample holder configurations.

B. DATA AND RESULTS

The objectives and requirements of the contract were to demonstrate the feasibility of converting electromagnetic waves in the microwave range to electricity at efficiencies higher than those obtained by solid-state converters and demonstrate the feasibility of using this conversion technique at solar and light frequencies.

Again the presentation of the data and results will be divided into the four ranges of experimentation.

1. 0.2 to 3.0 GHz

2. 10 GHz

3. 100 GHz

4. Solar/Light Range

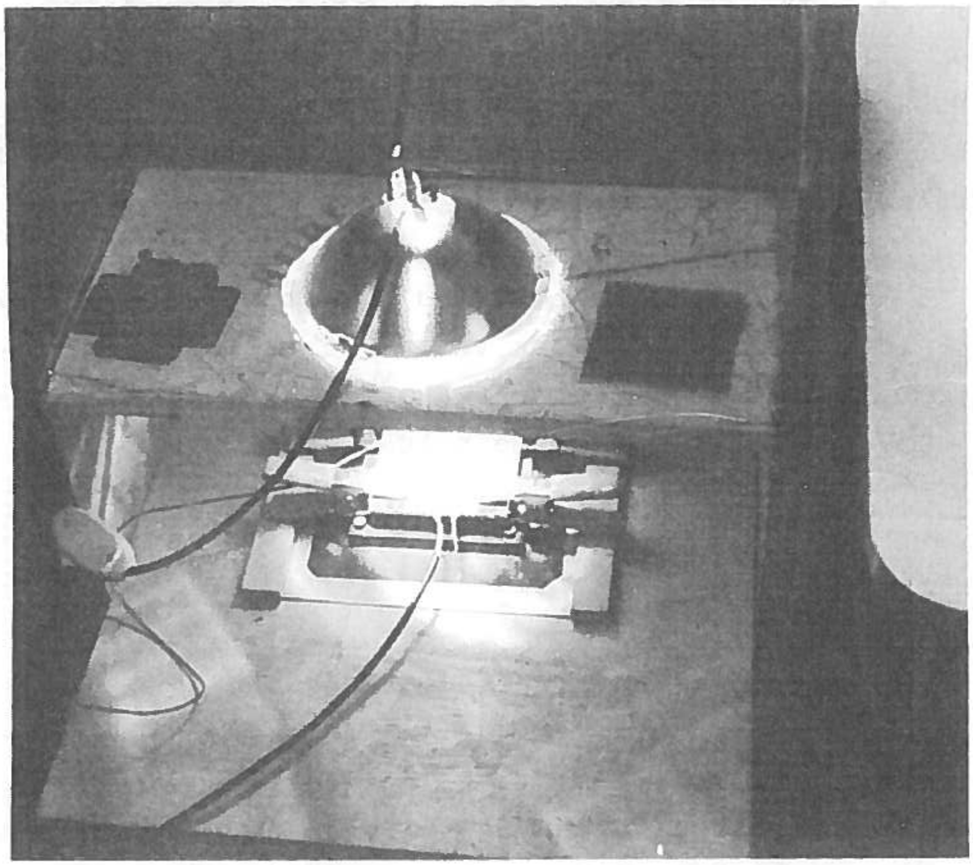


Figure 39. Solar/Light Converter Under Single Lamp Light Irradiation

Figure 40. Evaluation of Three-Lamp
Solar/Light Converter

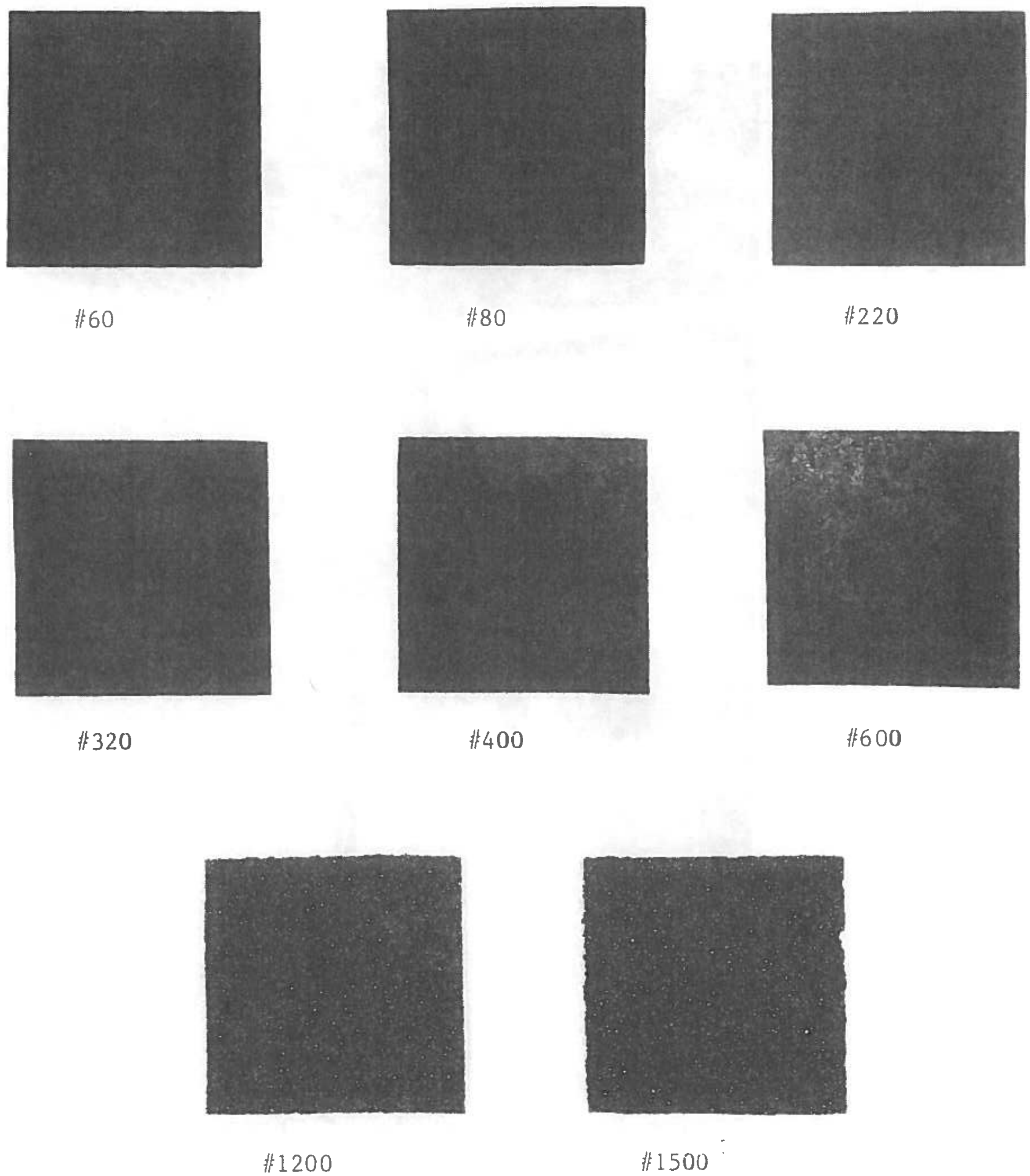


Figure 41. SiC Converter Samples

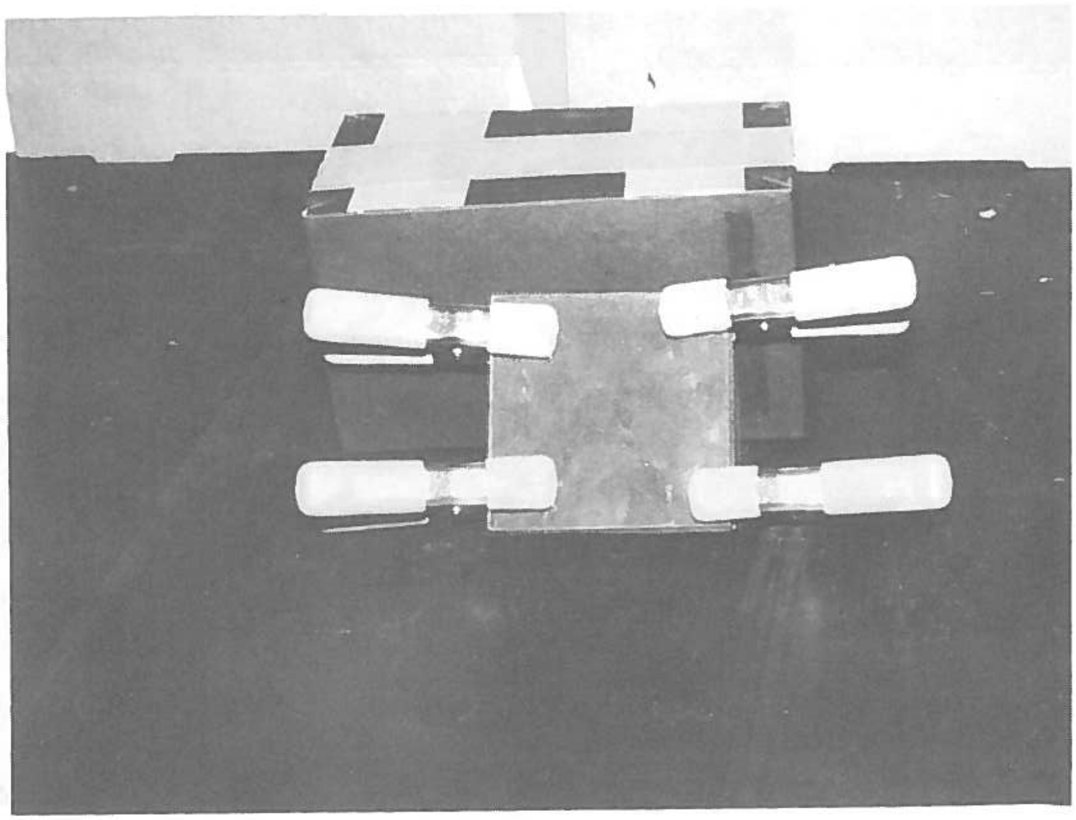


Figure 42. Square Solar/Light to Electricity Converter

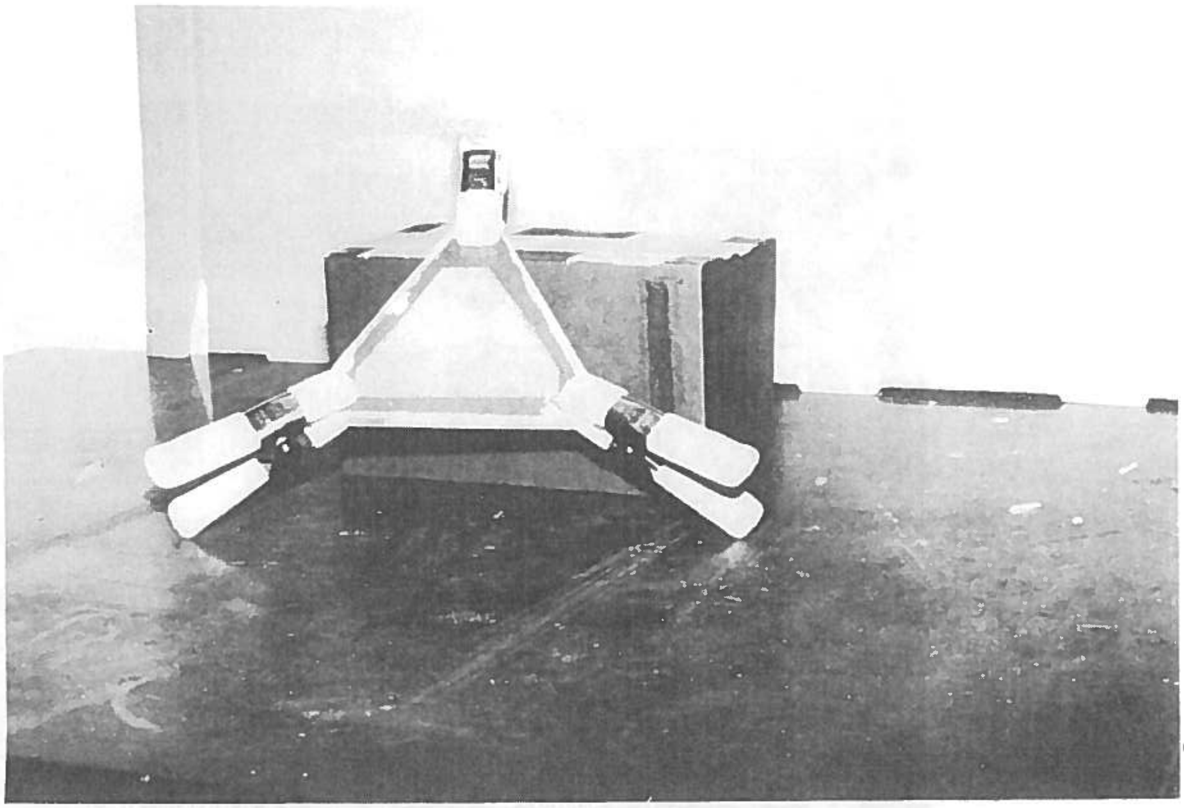


Figure 43. Triangular Solar/Light to Electricity Converter

1. 0.2 to 3.0 GHz

The experimental arrangement for the evaluation experiments in the 0.2 to 3.0 GHz range are shown in Figures 32 through 35. The field-strength meter was used to measure the energy in the beam, and both the Spectrum Analyzer and the power meter were used to measure the electrical output of the antenna-converter. As a third check for beam energy, an rpm versus power curve was determined for a small electric motor, and its rpm were then used to determine the power delivered to it by the antennae-converters.

All three arrangements produced essentially the same experimental results and checked against each other. The data will be discussed in detail in the Section IV. Overall system conversion efficiencies in excess of 60 percent were experimentally obtained, proving the feasibility of antenna conversion and supporting the theoretically obtained predictions.

The polar diagrams were obtained for a dipole, a pyramid, a cone, and a helix antenna. The results for one frequency (0.35 GHz), are shown in Figure 44. The plots for other frequencies are similar, giving the response to beams approaching the antennae from different directions. The actual absolute values vary with frequency.

Reflections of the microwave radiation off laboratory equipment and walls distorted some of the polar diagrams.

The response of the converter to the frequencies between about 0.2 and 3.0 GHz for three antenna geometries is presented in Figure 45. The variation of the power delivered is a function of the microwave energy in the microwave beam and depends on the frequency, the reflections from the surroundings and, the geometry of the converter.

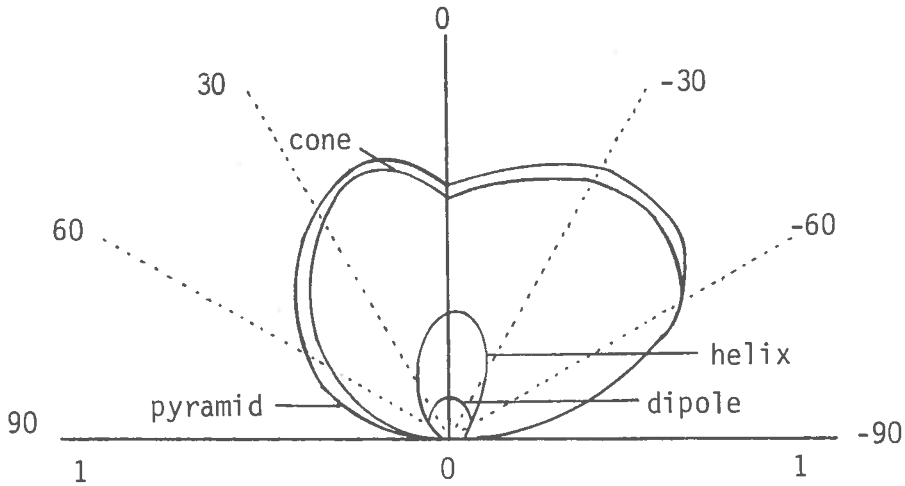


Figure 44. Polar Plots of 0.3 GHz Power Converters

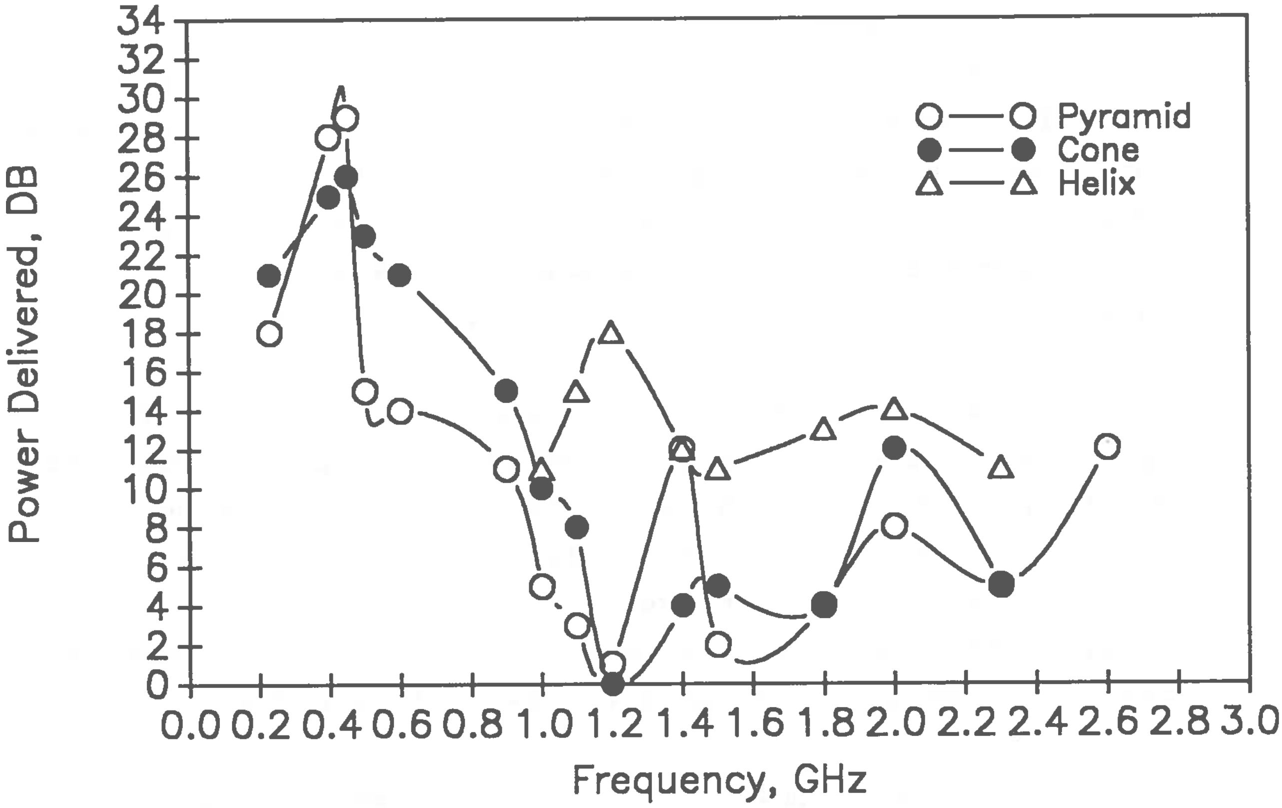


Figure 45. Frequency Response of Three Power Converter Configurations

As shown in the Energy Absorption Theory, with close spacing, almost all the energy falling upon a surface can be absorbed. This does not quite agree with antenna theory which predicts an optimum spacing between elements for maximum conversion efficiency.

Experimental work showed that, at the lower frequencies, some spacing (but less than predicted by the theory) gives maximum conversion. At the 10 GHz frequencies, the theory of energy absorption is supported by the experiments. However, not all the energy is absorbed because it is impossible to cover the total area with conical configurations. Pyramids should solve that problem.

Figure 46 presents the results for an array of pyramids of quarter wavelength design (8 cm on the side and 25 cm high). The signal was extracted about 1/4 side length from the point (the array was tuneable). Also shown is a three-truncated cone arrangement of dielectric material (10 wavelengths long, with a base circumference of 2 wavelengths, and a top circumference of 1 wavelength) tested at 10 GHz.

Since the conversion process can be separated into three parts; (1) the absorption of the energy, (a function of the geometry and materials), (2) the conversion to electricity and coupling to geometric shapes, and (3) (if DC is desired) the rectification of the AC output of the converter; it was decided to investigate each part separately.

The method described here and used in most of the work, combined at least absorption, conversion, and coupling into one process, giving the system conversion efficiency. When the DC electric motor was used, rectification had to be included in the process.

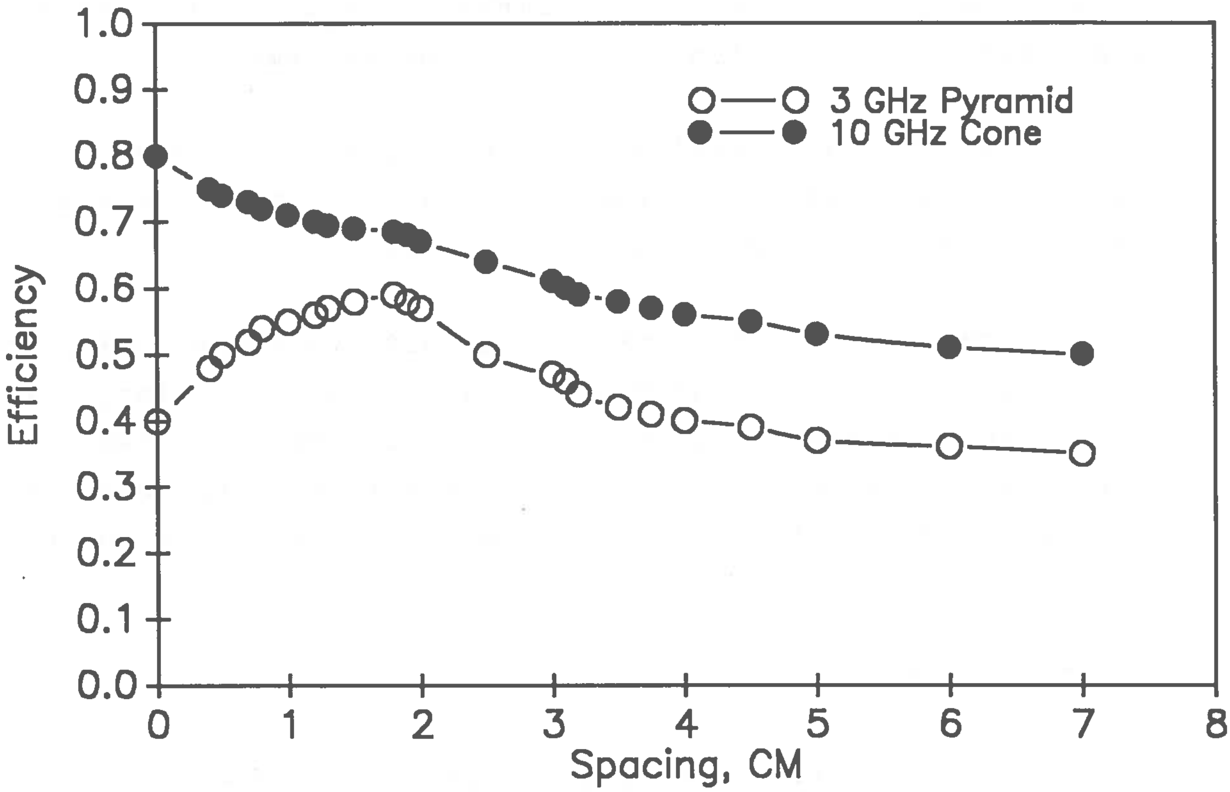


Figure 46. Spacing vs. Efficiency of Power Converters

In some of the experiments the microwaves are beamed across the laboratory and absorbed by the Electromagnetic Wave to Electricity Converter and its output is used to drive a small electric motor. This demonstrated the feasibility of transmitting power from one place to another without wires. This successful application requires efficient transmitting and efficient absorption and conversion systems.

With these experiments overall system efficiencies of over 60 percent were obtained, translating into estimated converter efficiencies of about 85 percent.

The wavelength in the 0.2 to 3.0 GHz range varies from over 1 meter to 10 cm and does not allow for large length to width ratios since the test elements would be too large to fit into the laboratory. For these reasons it was necessary to go to higher frequencies which allow miniaturization of these converter elements and arrays.

2. 10 GHz

The results in the 0.2 to 3.0 GHz range were very encouraging and higher microwave frequencies were needed for maximum flexibility in design.

To minimize costs equipment used for a different project (the moisture content determination of Space Shuttle Tiles (NASA)), was also employed in this investigation.

The equipment consisted of the 10 GHz microwave generator, detectors with analog readout, field strength meters, and various waveguide, antenna element and antenna array configurations. This frequency allowed miniaturization of up to two orders of magnitude.

After determining the beam energy, different geometric antenna configurations were inserted in the beam and Amplification Factors were determined. After the optimum geometry was obtained the next step, extracting the energy from the elements or arrays by differently designed probes coupled to the elements, had to be determined.

The equipment used is shown in Figure 47: a 10 GHz generator, a dielectric waveguide (made of paper and waxed) and the field strength or intensity meter.

Many of the waveguides were patterned after nature, or insect antennae. Scale models of some insect antennae, (USDA) are shown in Figure 48. Some of these, although not designed for the 10 GHz frequency, were used in the experimental investigation.

Some of the dielectric configurations used are shown in Figure 49. A number of these waveguides have the same base circumference but are different multiples of wavelength in length. The base circumference in many is 1 wavelength.

Figure 32 shows a waveguide, a truncated cone with the base circumference being 2 wavelengths and the small end circumference one wavelength. The element is 10 wavelengths long. Its polar plot is shown in Figure 50 presenting the Amplification Factors produced as a function of beam approach angle. This approach only investigates the geometry and is rather independent of the surroundings. Reflection of microwaves did not effect these data, but microwaves were troublesome in the experiments described earlier, with wavelength one to two orders of magnitude longer.

Figure 51 presents experimental data obtained with the 10 GHz equipment. It gives the beam Amplification Factors for a single element truncated cone having a length of 10 beam

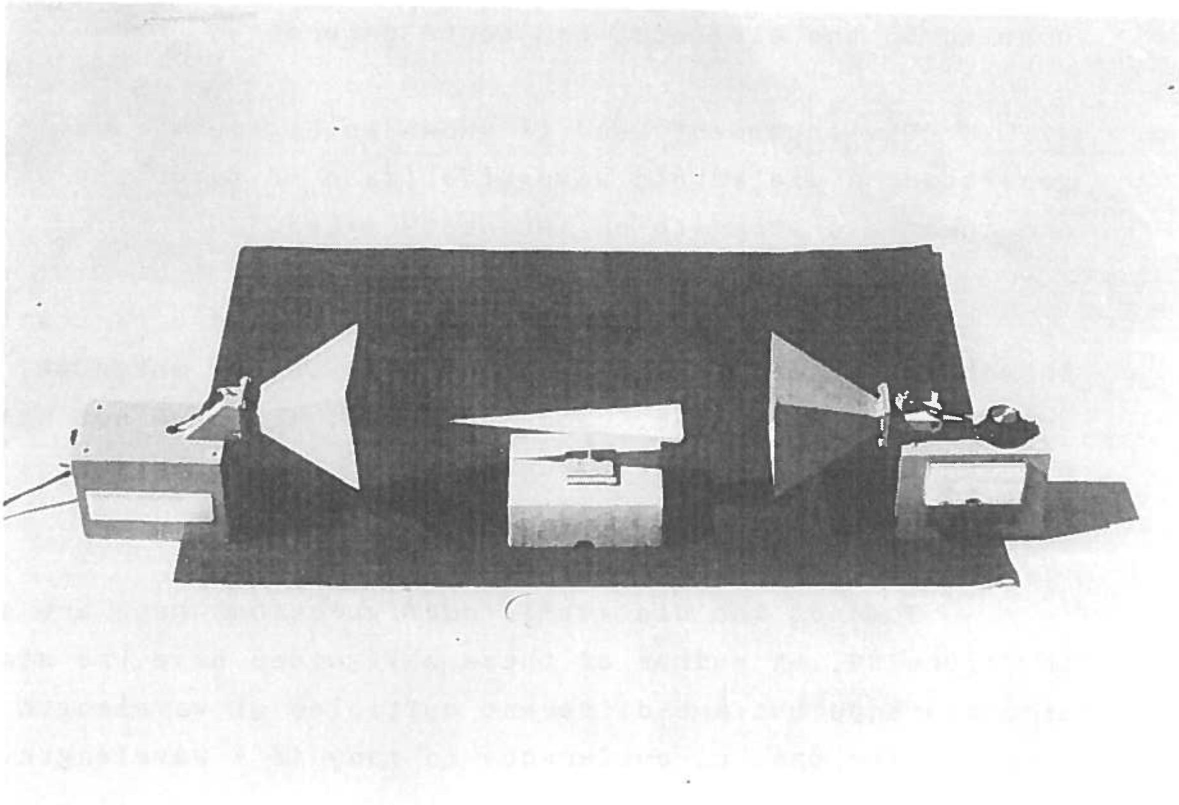


Figure 47. 10 GHz Microwave Test Guide with Dielectric Waveguide

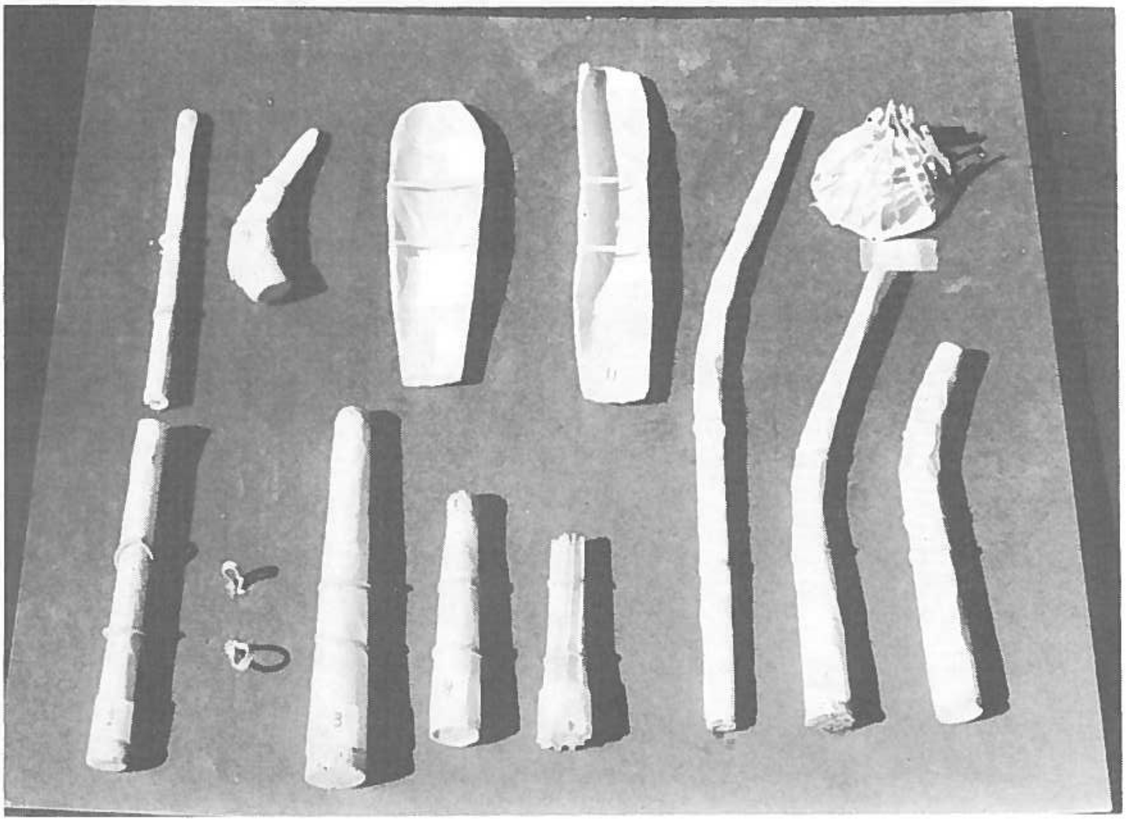


Figure 48. Scale Models Insect Antennae

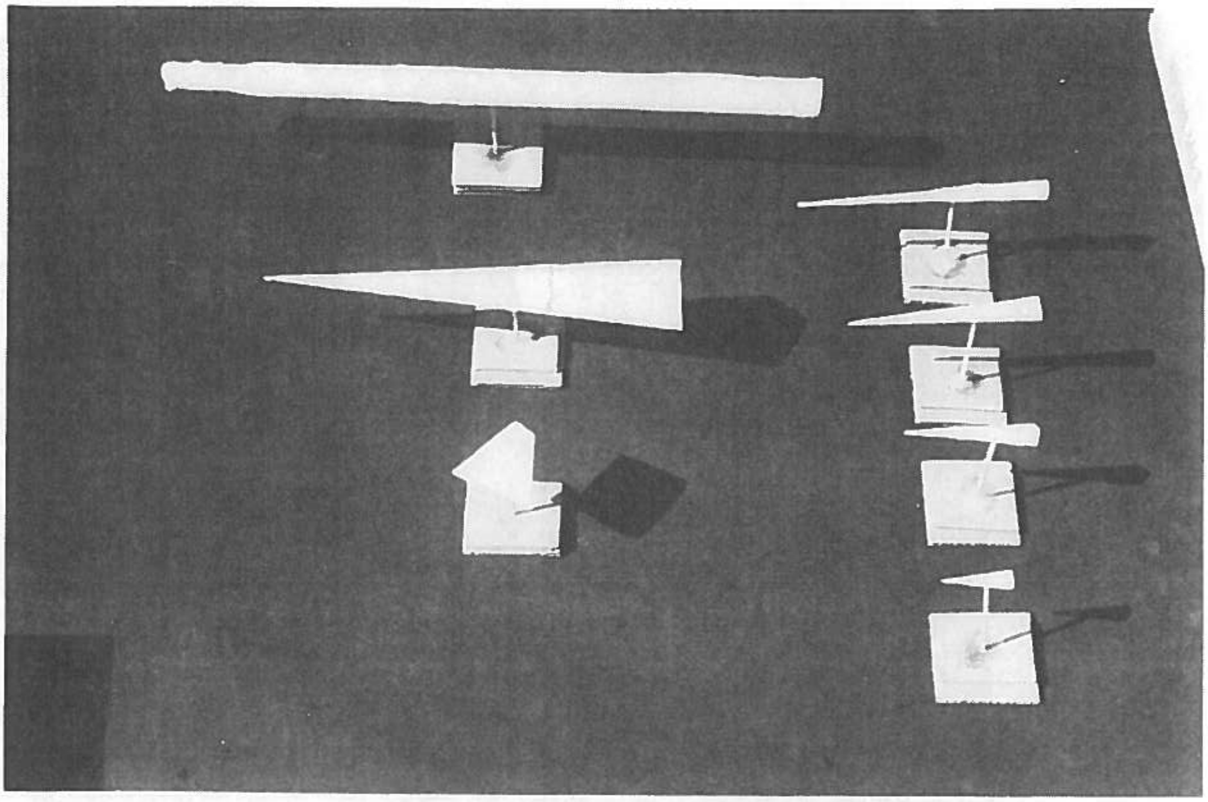


Figure 49. Various Geometries of Dielectric Power Converters

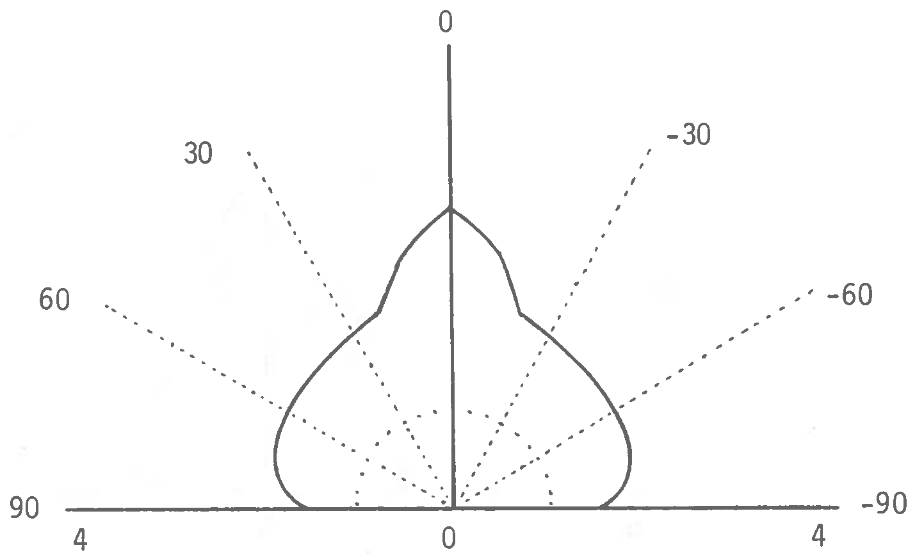
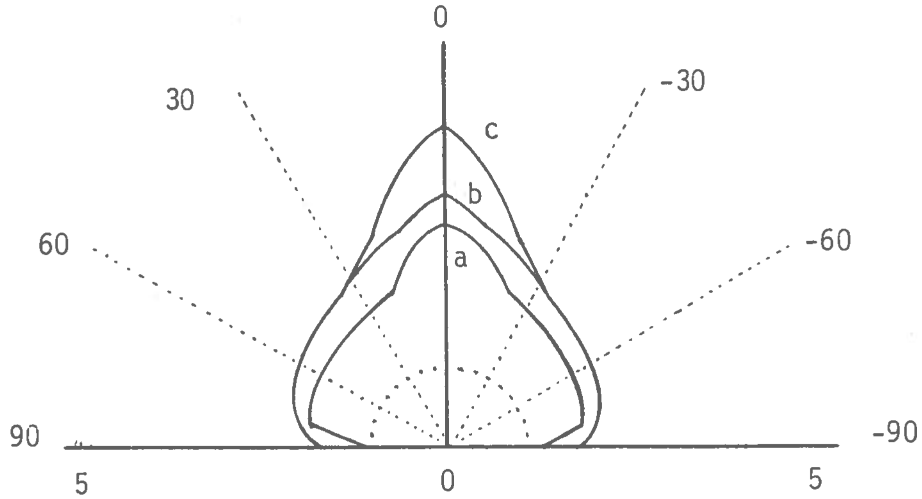


Figure 50. Polar Plot for 10 GHz
Truncated Cone Power Converter



a= single element
b= 3 element ½ λ spacing
c= 3 element 0 spacing

Figure 51. Polar Plot of Various Spacing For Power Converters

energy wavelengths, a base circumference of 2 wavelengths and a top circumference of 1 wavelength. (Curve A).

When three of these elements are used and spaced according to antenna theory, their experimental beam amplification factor is given in Curve B. The efficiency is increased over a single-element converter. The three-element configuration was selected because its pattern can be extended to collection areas of any desired size. This is accomplished by simply adding elements with the same spacing configuration as the three basic ones.

As mentioned earlier, the contradictory requirements between antenna theory (which requires definite spacing of the elements) and the absorption theory, as pertaining to energy (which requires close spacing) is tested experimentally in this investigation and presented in Figure 51. The beam power Amplification Factor is greatest for the three-element configuration when the elements are spaced as close as physically possible. The three elements are touching at the base, with their axes parallel.

The beam power amplification factor is a function of spacing as predicted by both theories, but seems to agree with the Energy Absorption theory. This theory says that the amount of energy collected increases with a decrease in spacing, or in other words, tight configurations leaving no open spaces for energy to penetrate, give the maximum absorption and therefore, conversion efficiency.

Figure 52 shows an insect antennae array under test. This array has interesting characteristics. This insect antenna array scale model modulates the 10 GHz microwave beam when moved along the beam between generator and detector. The amplification increases and decreases with movement in the axial direction.

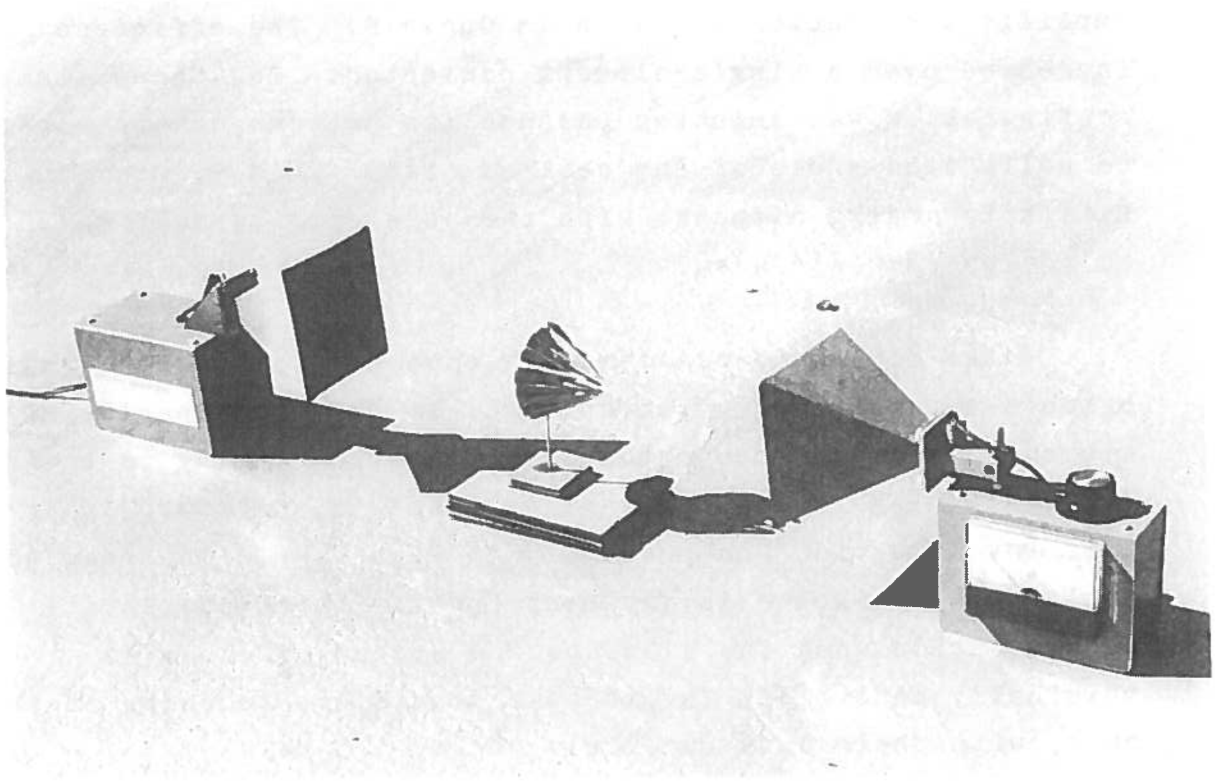


Figure 52. Evaluation of Scale Model of Insect Antenna Array

Much more data have been been collected on different configurations (rods, tubes, etc.) but all seem to have the same basic characteristics as those presented here.

After the optimum geometry, etc., is determined in and through this investigation it will be necessary to construct these ideal geometries in sizes for solar energy conversion.

Data and information on some of the more important basic characteristics, for both the individual elements and antenna arrays are presented here and further discussed in Section IV.

a. Length Over Base Dimensions Ratio

To obtain the information upon which to determine the length to base dimension ratio the base dimension was held constant and the length was varied, then the length was held constant and the base dimension varied. The basic characteristics in both sets of these experiments were the same and only the absolute values varied as the actual size of the antenna element varied. The optimum was obtained with the base dimension equal to 1 wavelength.

Figure 53 shows how the Amplification Factor varies with an increase in length over base dimension ratio. These data are for the beam direction parallel to the axis of the antenna element.

b. Axial Position in Beam

Since the 10 GHz energy source produces electromagnetic waves of 3 cm wavelength, the position of the antenna element along the axis of the beam has some effect upon the performance.

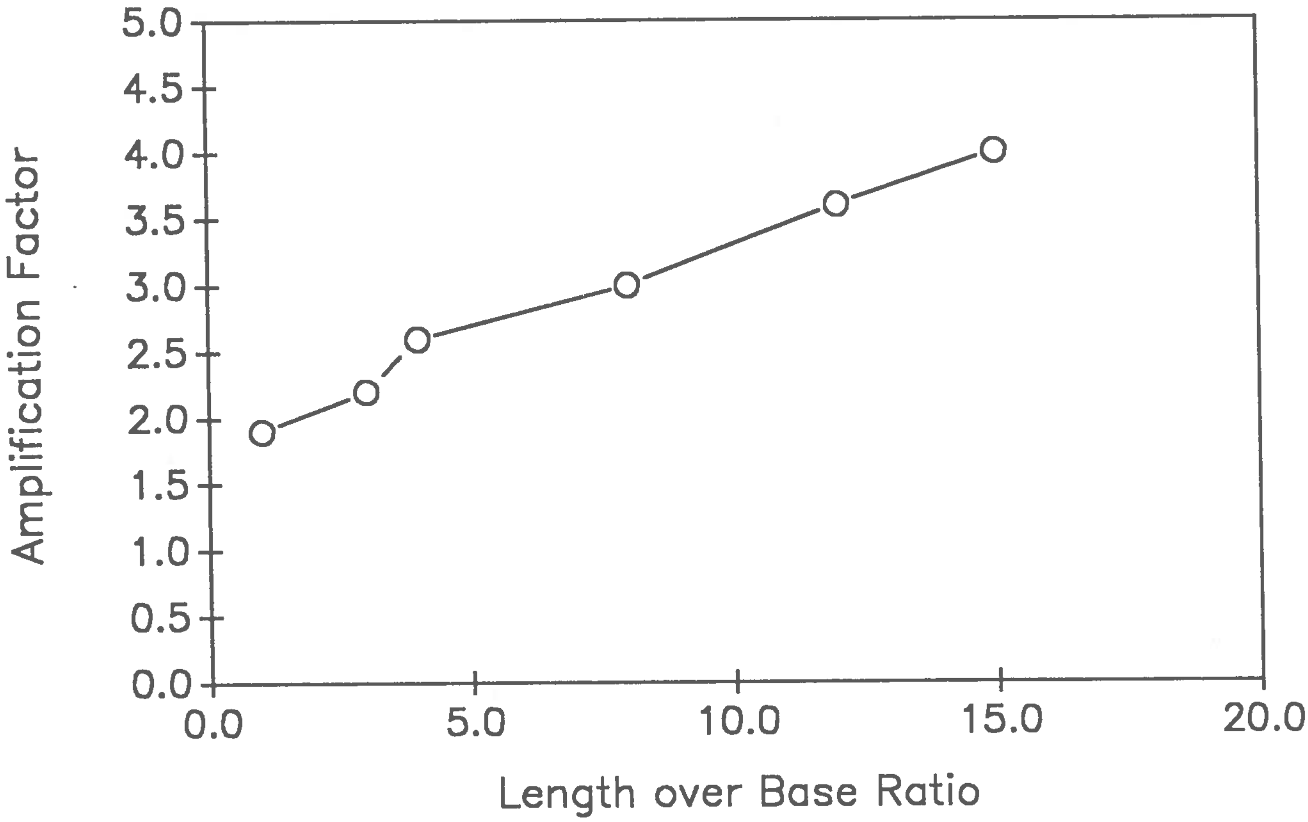


Figure 53. Amplification Factor as a Function of Length Over Base Ratio (10 GHz)

Figure 54 shows this variation for both a dielectric and a metallic element. The performance of the dielectric element is considerably better.

c. Wall Thickness of ASETEC Elements

The wall thickness of the antenna elements had considerable influence upon the performance, as expressed by the amplification factor. See Figure 55.

d. Spacing Between Antenna Elements

As was pointed out earlier, the antenna theory requires a definite spacing of the individual elements when arranged in an array, while the absorption theory requires close spacing with no holes or waste space between the elements.

At 10 GHz, the difference between the requirements of the two theories vanishes and the optimum design is based upon them coverging into one.

Figure 56 presents data substantiating this result. It shows best performance of a three-element array when the individual elements have zero spacing between them.

e. Number of Elements in an Array

Theory predicts that the performance of an antenna increases when the elements are arranged in an array.

Experiments were carried out with individual optimized antenna elements and then in arrays containing up to 16 individual elements.

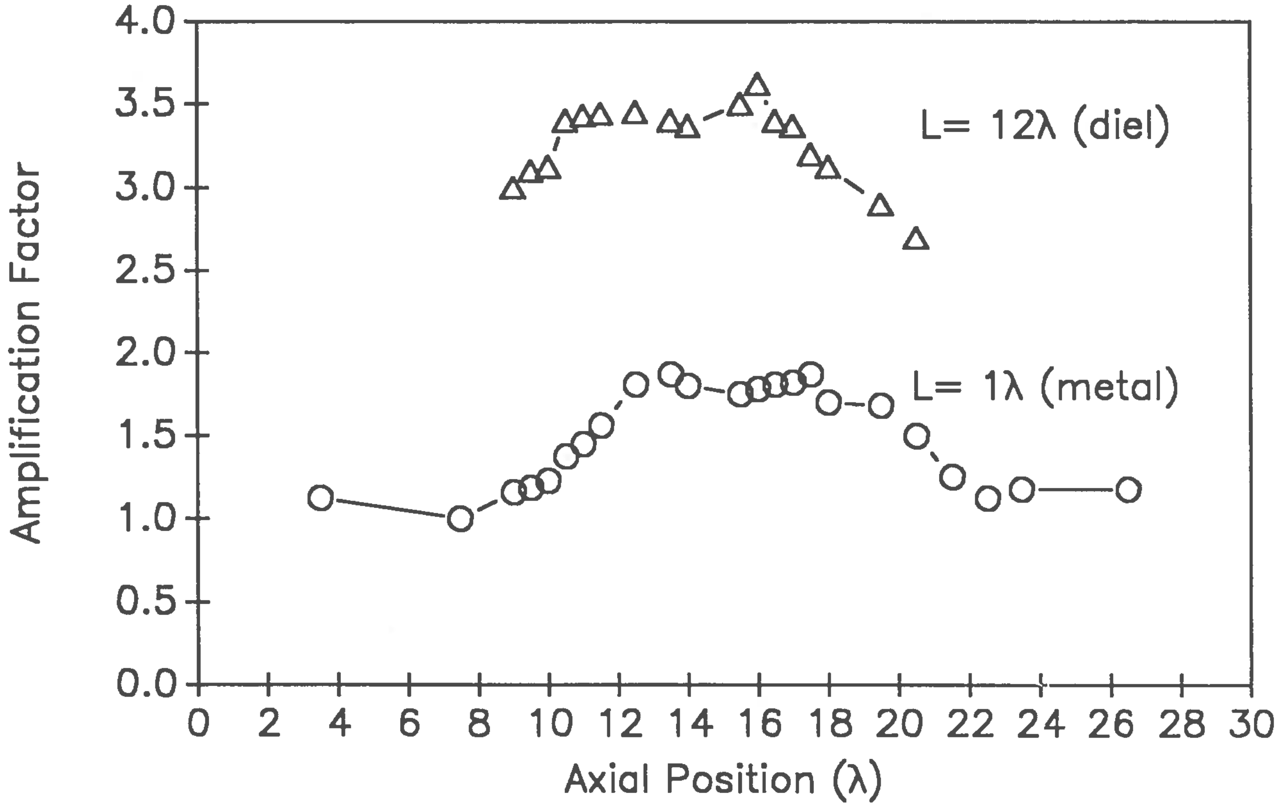


Figure 54. Amplification Factor vs. Axial Position for Dielectric and Metallic Converters (10 GHz)

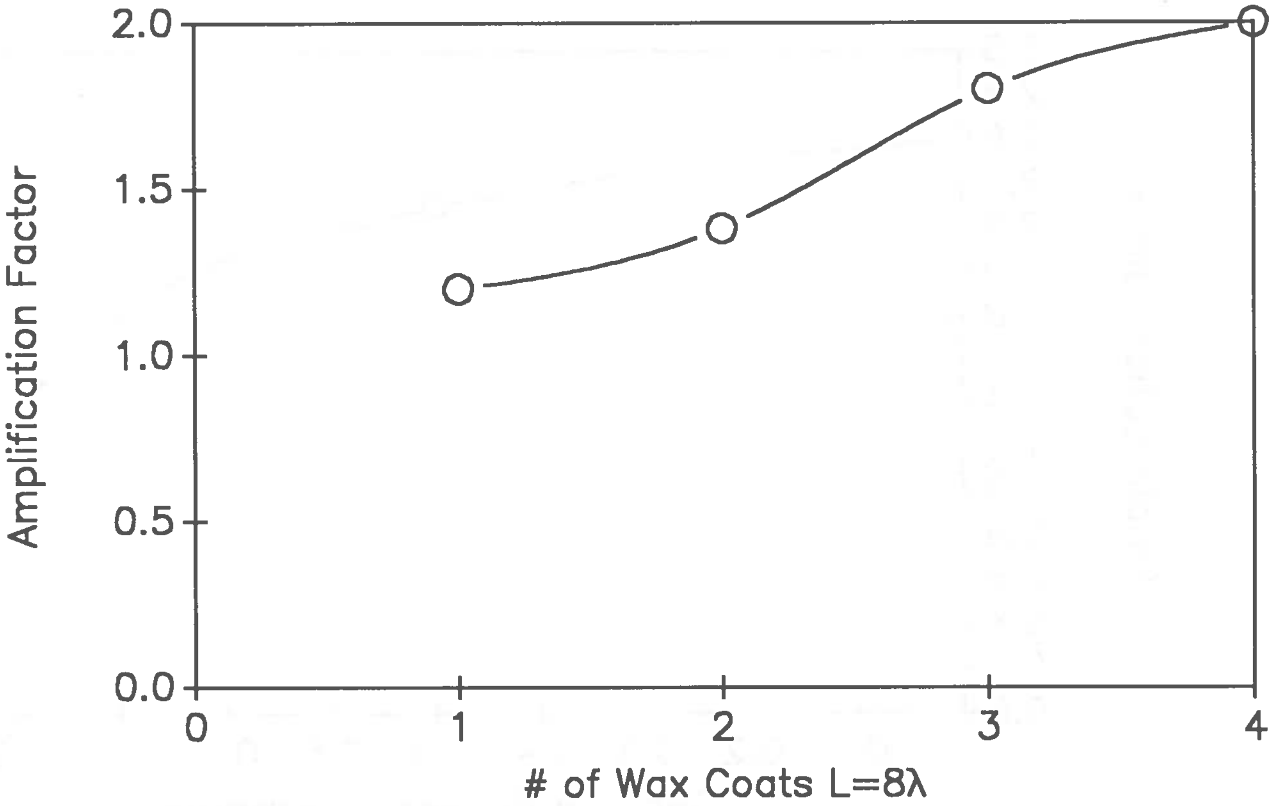


Figure 55. Amplification Factor vs. Wall Thickness of Antenna Element (10 GHz)

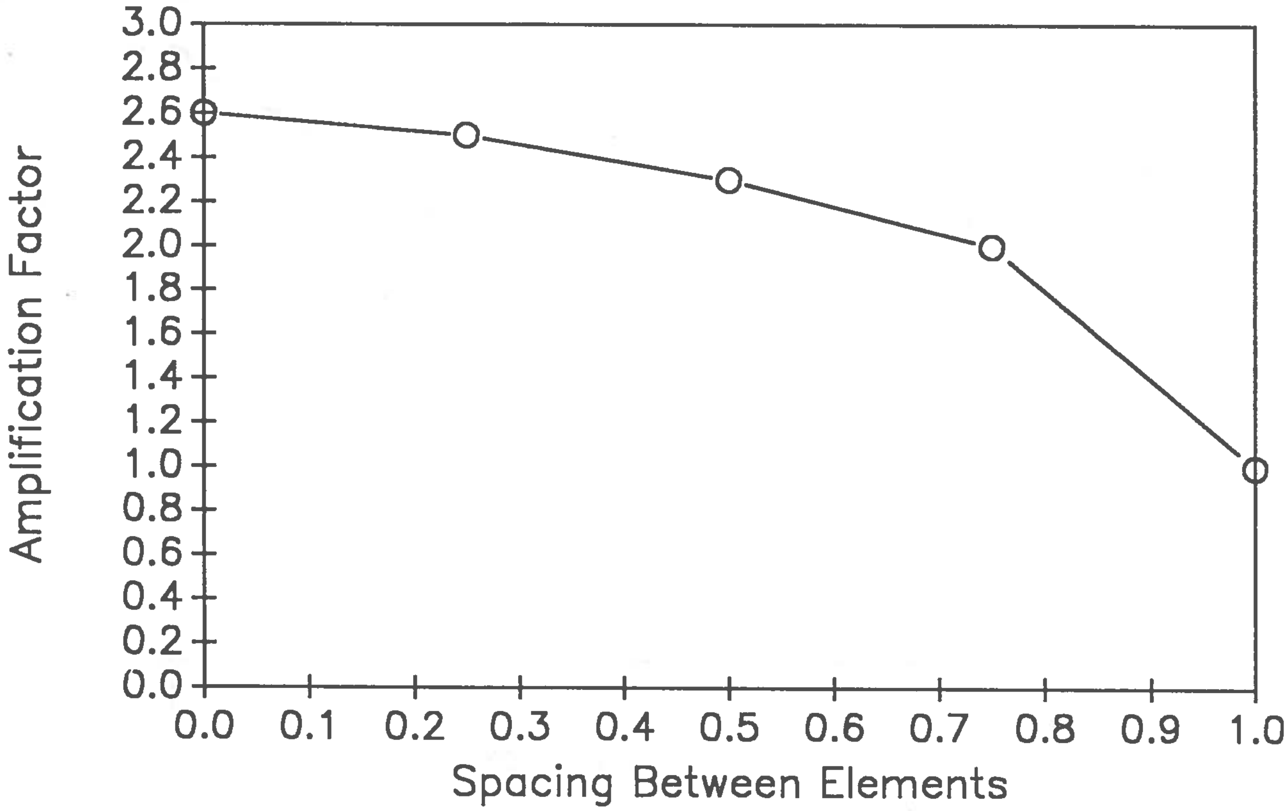


Figure 56. Amplification Factor vs. Spacing for Three-Element 10 GHz Power Converter.

Figure 57 presents the results of some of these experiments showing the increase of performance with number of elements in an array but this increase occurs at a decelerating rate.

f. Coupling to the Antenna Elements

(1) Type of Probes

A number of different probes were used to couple to the antennae elements and extract the collected and converted energy from the antennae.

For the experimentation carried out in this investigation straight wire, arrowhead, inverted arrowhead, Tee shaped, three pronged, and disc probes were used as shown in Figure 58.

The results presented in Figure 59 show that the three-pronged probes and the disc probes performed best.

(2) Position of Probe in the Element

Theory predicts that the position of the probes for best performance should be on the axis of the element and one-fourth element length from the point of the element.

The results from the experimental investigation, (Figure 60) show that the position predicted by theory works well but the position used by nature, in the configurations of insect antennae, where the probe is located at the base works even better.

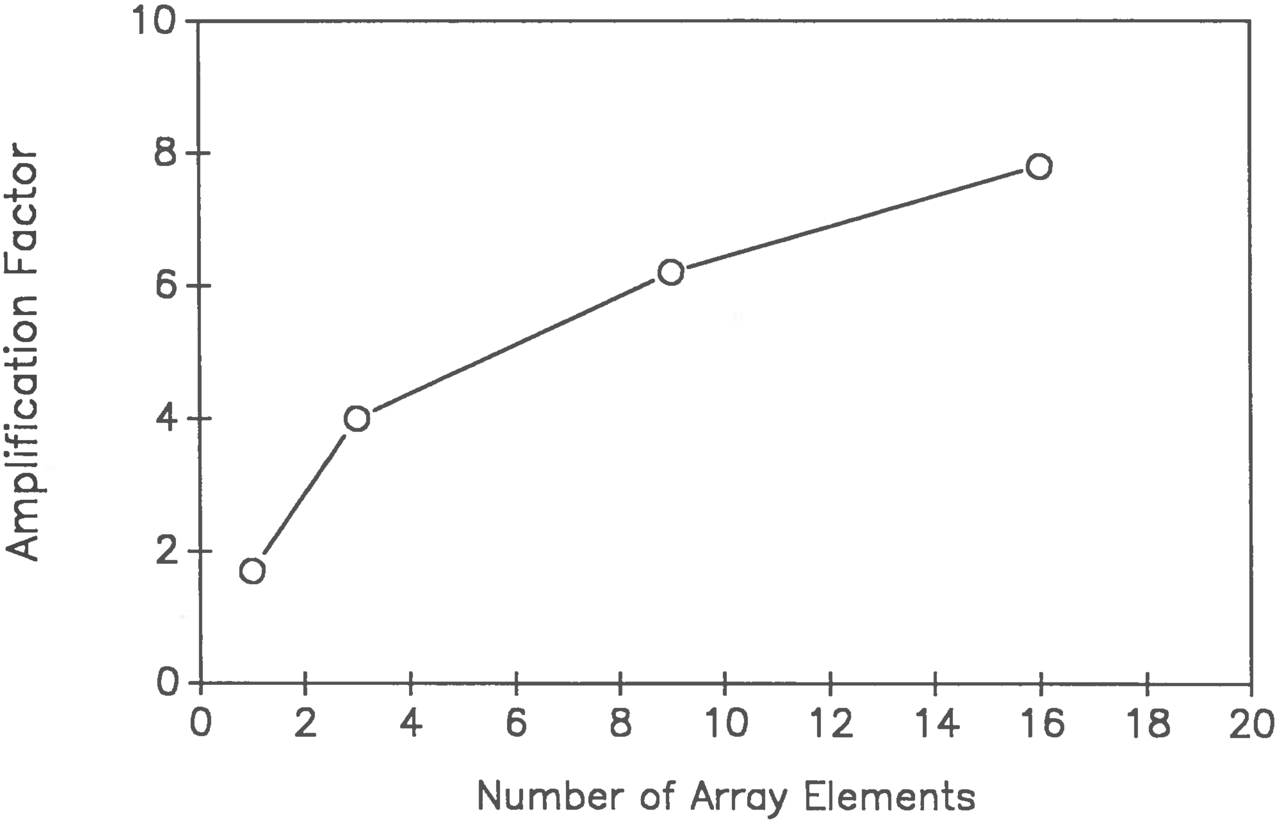


Figure 57. Amplification Factor Based Upon Number of Elements in a 10 GHz Array

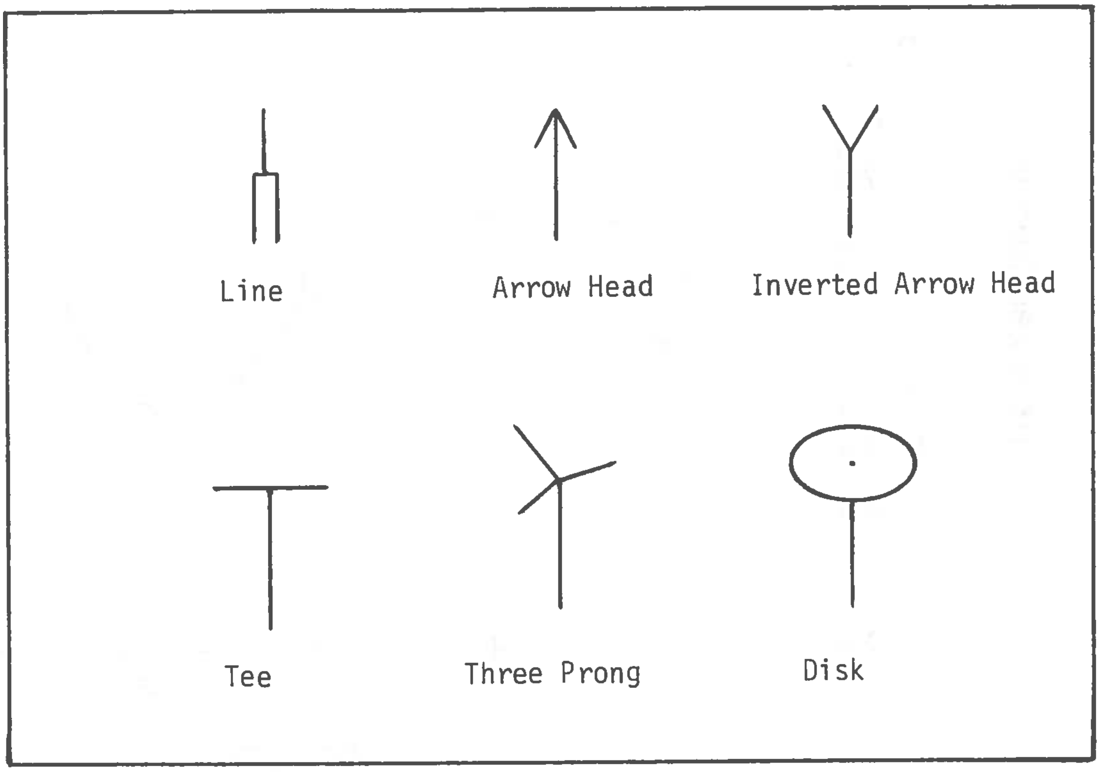


Figure 58. Probe Types

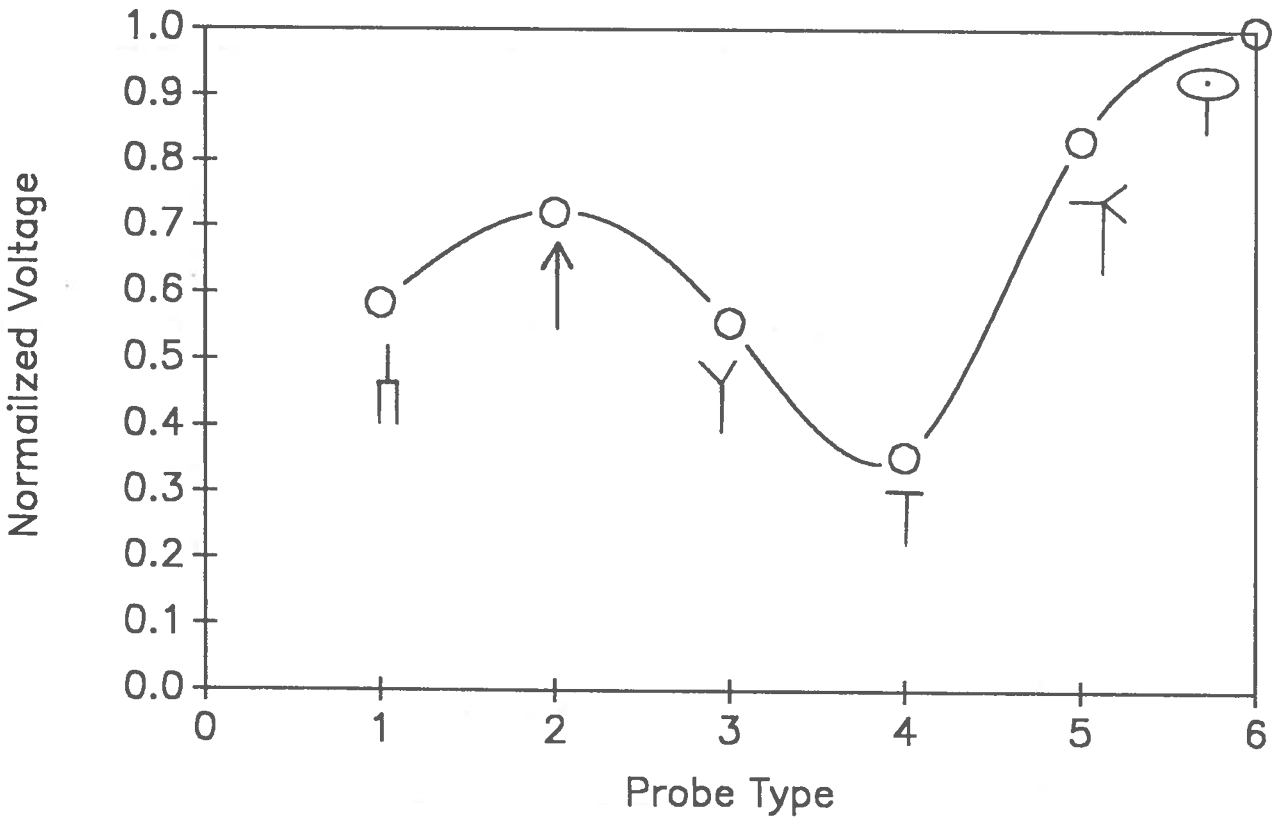


Figure 59. Performance of Various Probe Couplings

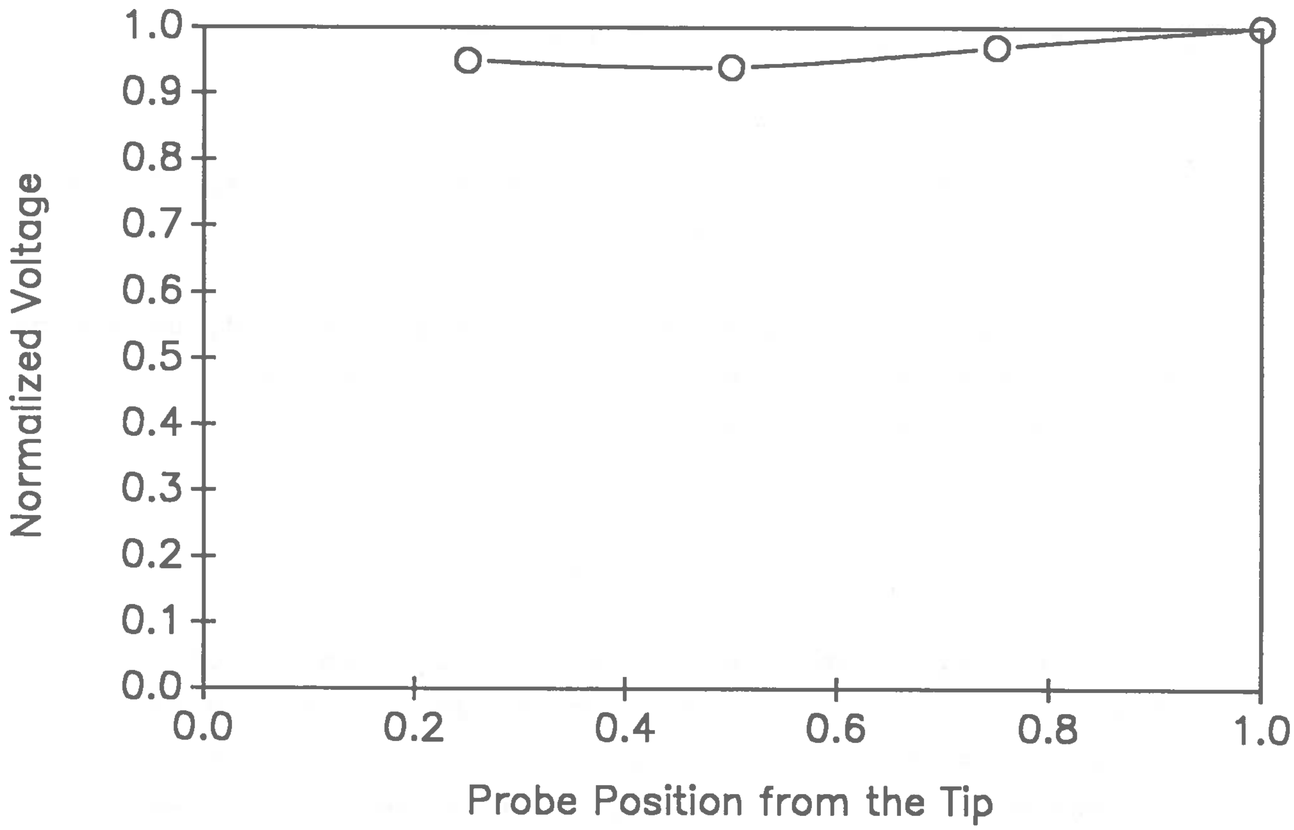


Figure 60. Normalized Voltage for Probe Position

3. 100 GHz

The work with the 100 GHz equipment, was primarily used to find out if the basic characteristics of the performance change with wavelength. At 100 GHz the wavelength of the electromagnetic wave produced by the generating equipment is 3 mm.

The work carried out here showed no significant change in results from the work carried out with 10 GHz.

This result was expected and, when verified, only spot checks were made with the optimized antenna element configurations and arrays.

4. Solar and Light Energy Conversion

Having established the design requirements of antennae arrays in the conversion of solar energy to electricity through the microwave studies, it has been shown that the wavelength has little effect upon the conversion process, as long as the antennae are scaled properly.

The next step was to show that the conversion can be carried out at solar and light frequencies.

Rather than spending the time and finding funds (no funds were available in this phase of this contract) to manufacture antennae arrays for solar and light frequencies, it was decided to utilize Carborundum® paper. It has pyramid-shaped crystals, which are crushed and then mounted on paper in different grain sizes and used for finishing surfaces of materials.

This is an inexpensive source of a random array which can be used in investigating the basic performance of more perfectly shaped arrays when they are fabricated.

a. Grain Size

A series of different numbered Carborundum® papers, 60 through 1500, covering grain sizes from about 500 down to 7 microns were prepared so that collectors could be attached to them. These papers were exposed to sunlight and artificial light and their electrical output was measured.

Figure 61 gives the voltage generated by the conversion process as a function of grain size. The output increases as the grain size decreases and finally approaches the theoretically optimum size.

Since, in the Carborundum® papers, the grain size is not perfectly controlled its distribution (which is typical for all the papers) for number 80 is shown in Figure 62.

b. Collector Spacing

The electricity generated by the conversion process is picked up by collector wires which are arranged as a grid with different spacing.

The effect of collector grid spacing upon the output is shown in Figure 63. The maximum is observed with a grid spacing of about 1/10 of an inch.

c. Solar or Light Intensity

Solar Energy was used in enough experiments to prove that the conversion works. Most of the experiments used incandescent light sources, powered by AC, but stray fields

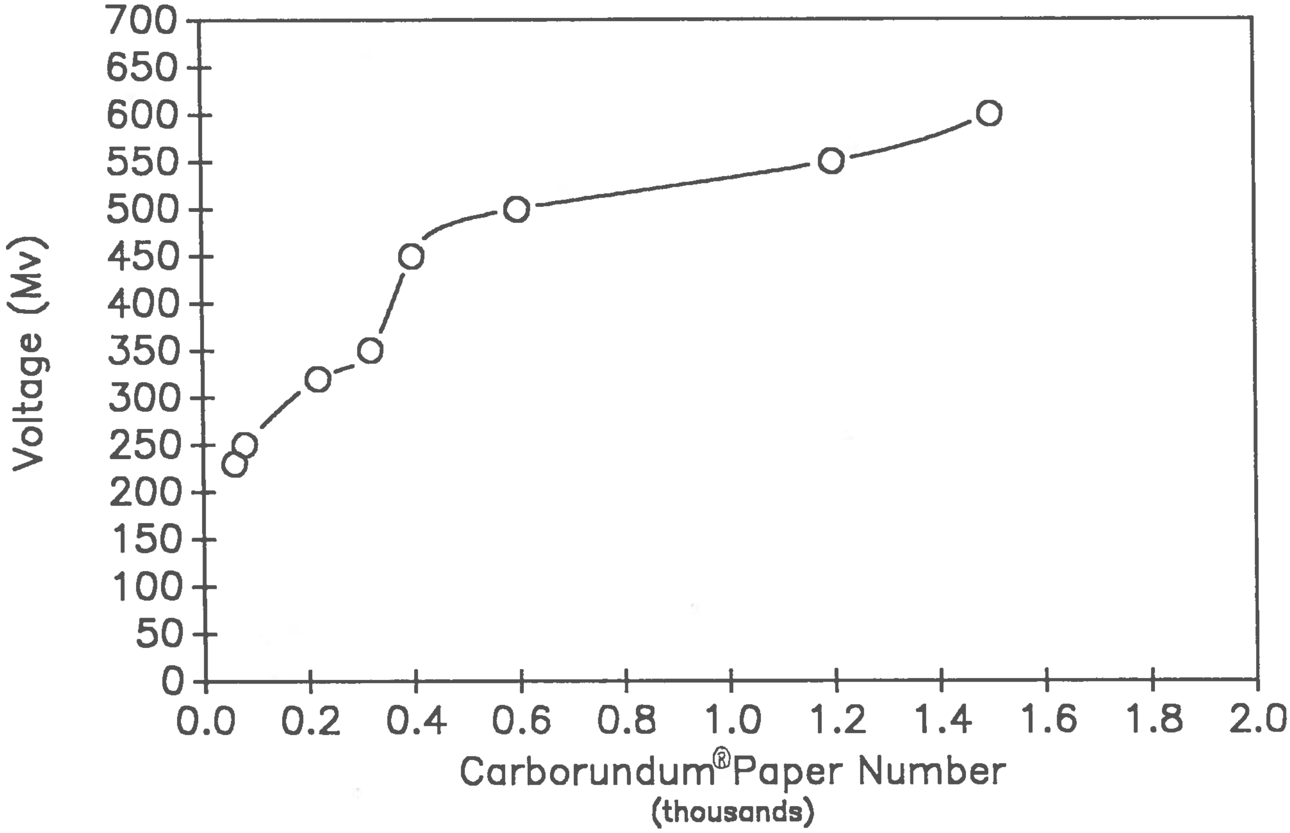


Figure 61. Voltage vs. Grain Size as Determined by Carborundum® Paper Number

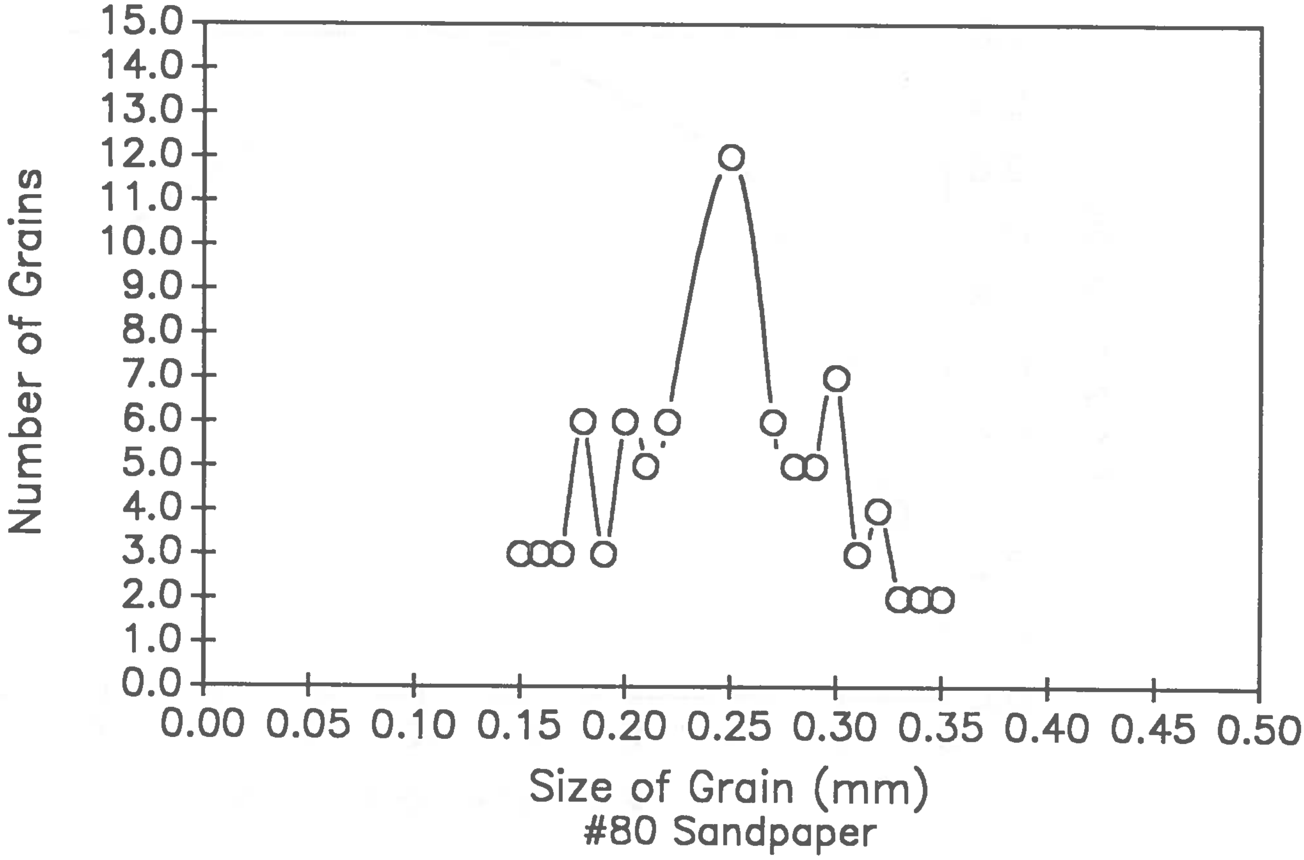


Figure 62. Grain Size Distribution

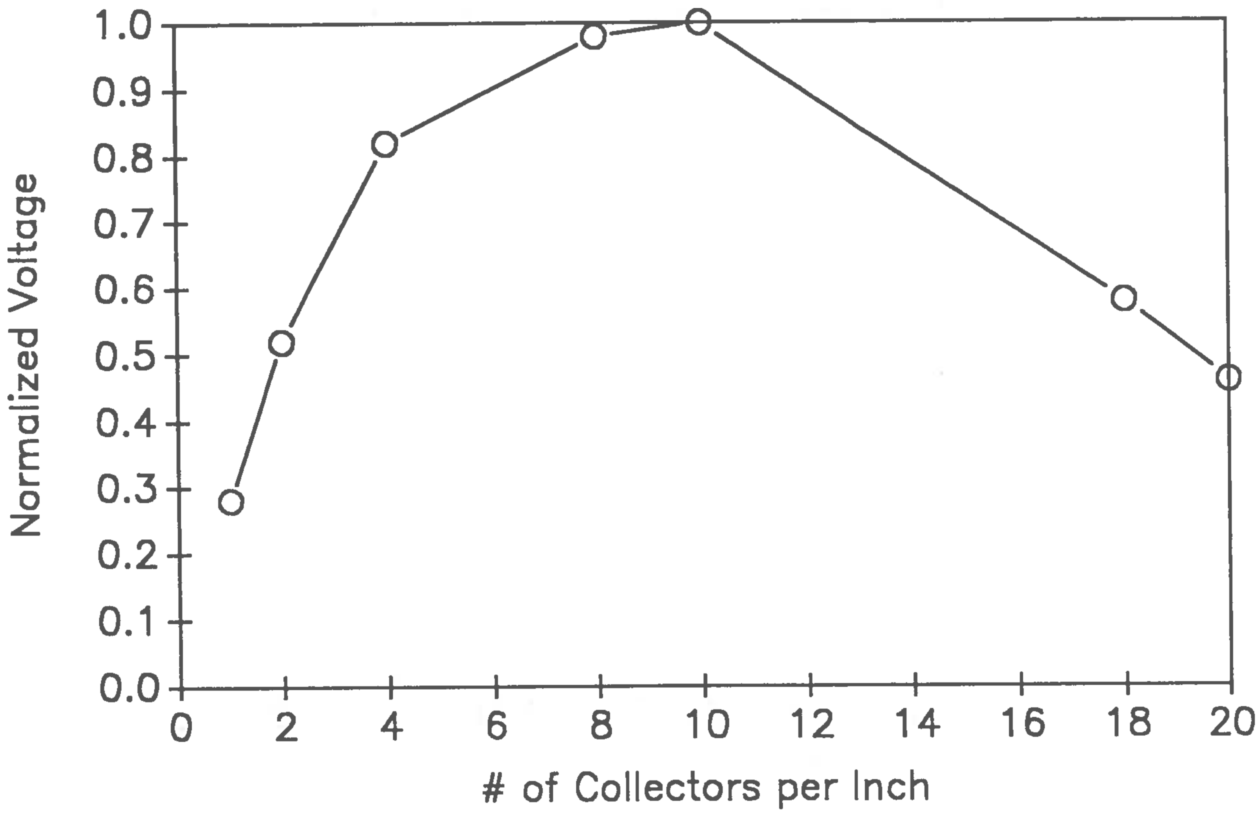


Figure 63. Normalized Voltage vs. Number of Collectors

made measurements difficult. A 12-volt battery was then substituted and automobile sealbeam headlights were used.

The intensity was changed by changing the distance between the light source and the target converter.

The decrease in output with decrease in light intensity is shown in Figure 64.

d. Contact Pressure

The collector wires were pressed against the grains of the Carborundum® paper on one side by the transparent glass or sheet of plastic and the other side by a board. The contact pressure was controlled by thumbscrews in the four corners.

Light pressure produced lower output but as soon as a critical pressure was reached the output stabilized and did not change with further increase in pressure.

Figure 65 presents the results of this effect.

e. Impedance Matching

The energy intensities of the beam radiation were small and the electrical output after the conversion was smaller so that even the instrumentation put a load on the converter during the measurement.

Additional loads were put upon the converter and it can be shown that the output increases up to a point by having a better impedance match at the right load.

Figure 66 gives the results of this part of the investigation.

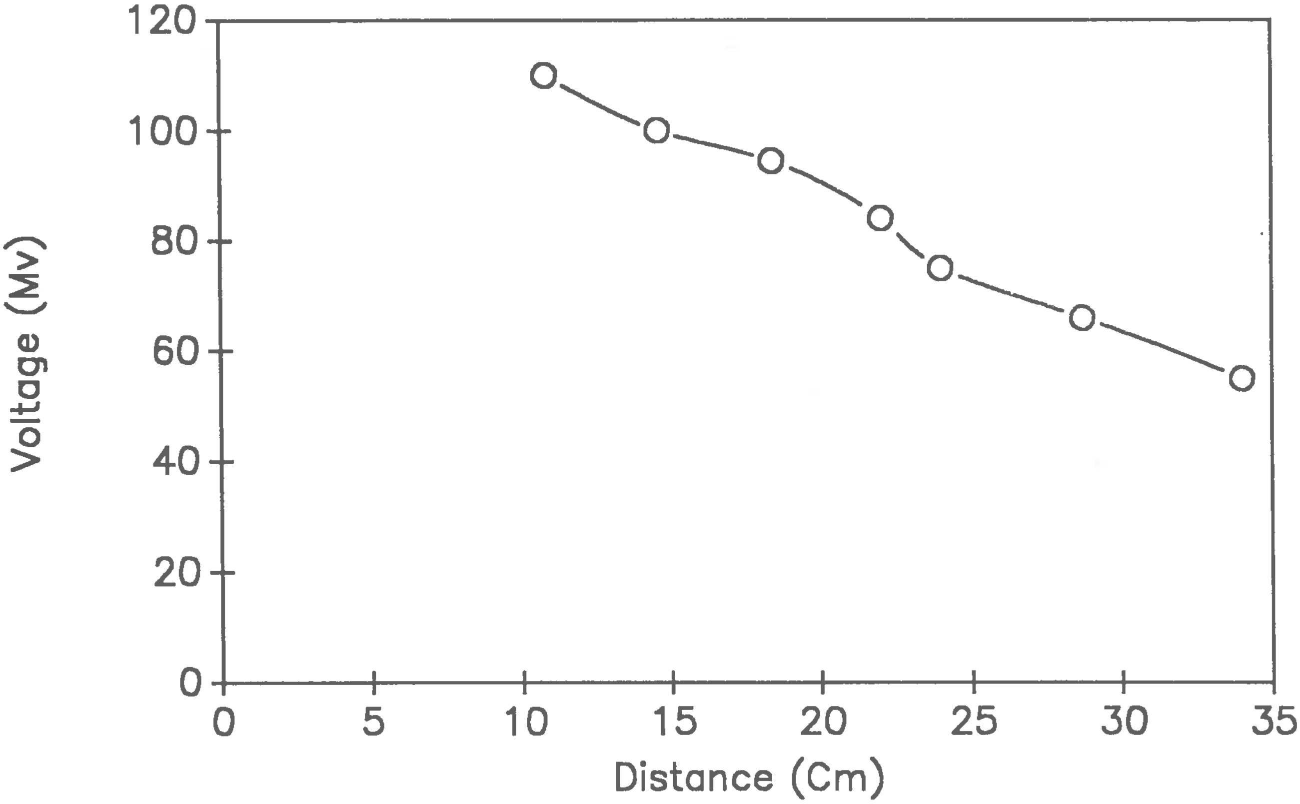


Figure 64. Effect of Radiation Intensity upon Performance

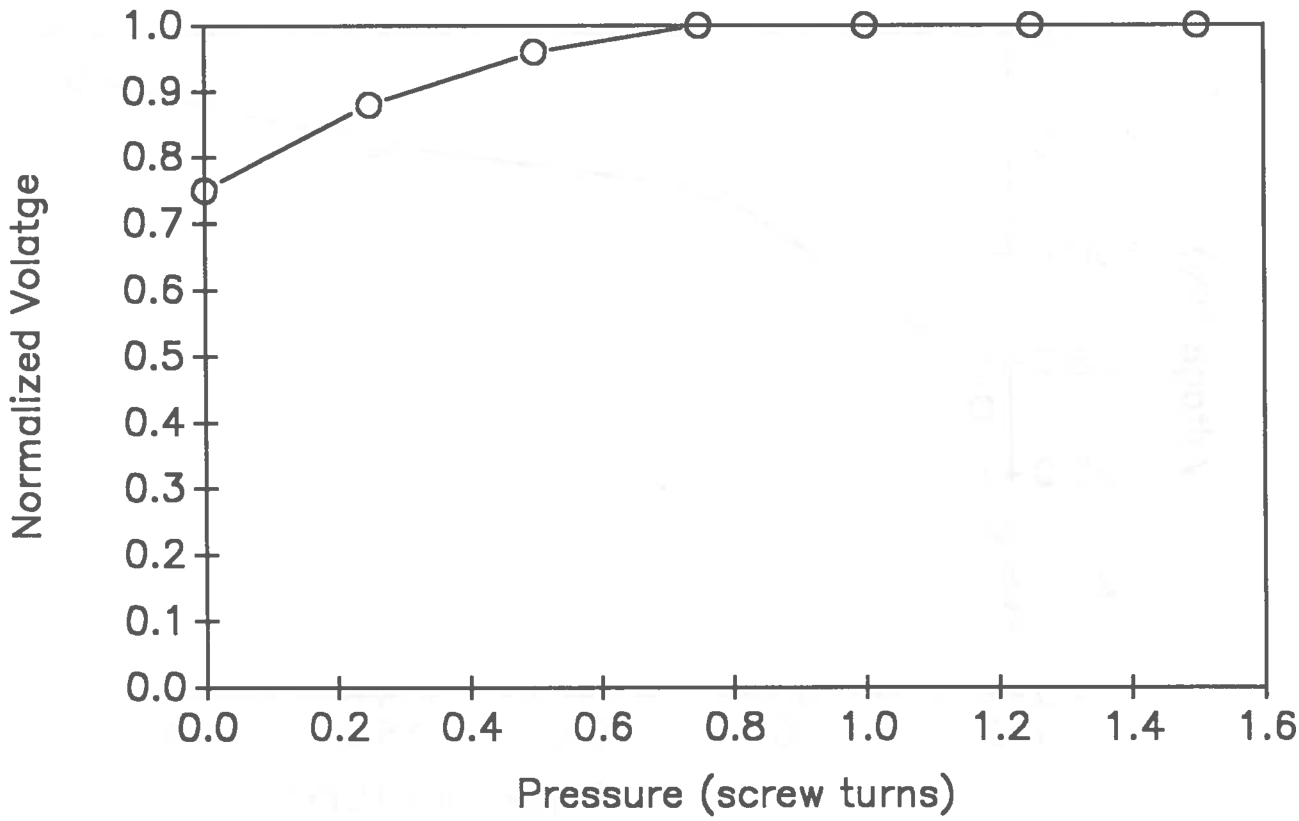


Figure 65. Effect of Contact Pressure upon Collector Performance

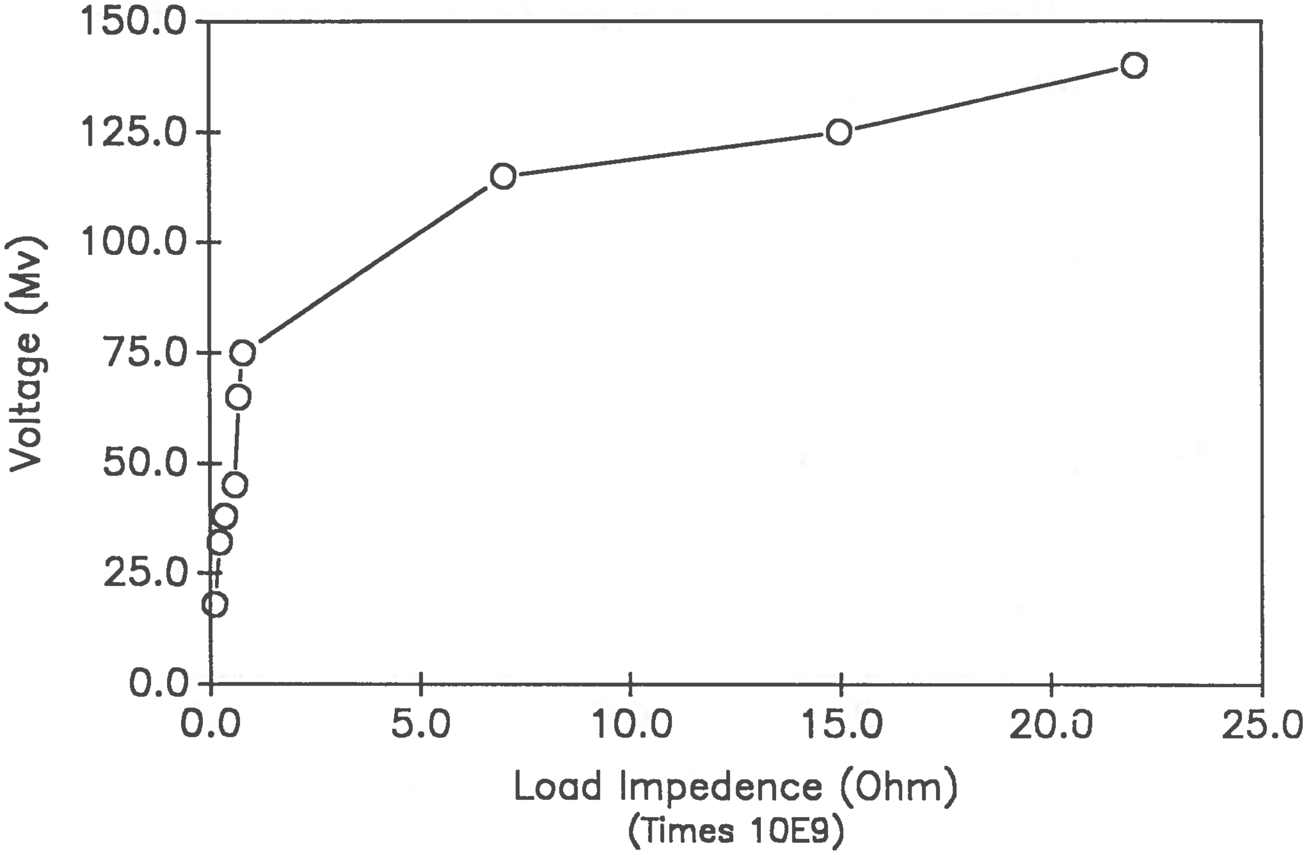


Figure 66. Effect of Matching Load Impedance to Converter

f. Temperature Effect

As the converter was exposed to the radiation source (solar or incandescent lights) its temperature slowly increased. It is believed that the binder material holding the grains softened and some of the grains rearranged themselves (a fact also observable under the microscope) and therefore the physical configuration changed producing different results.

Figure 67 shows the changes in temperature with time of exposure. These curves naturally vary with radiation intensity.

g. Voltage Output Variation with Exposure Time

The variation of voltage with exposure time was typical for the intensities of radiation encountered with solar energy as the source. The voltage output increased reaching a maximum then dropping and reaching a steady value from then on.

This variation and behavior can be correlated with the temperature variation due to the exposure to radiation. See Figure 68.

h. Output Voltage as Effected by Grain Size

Figure 69 presents the voltage versus time curves for six different grain sizes.

It can be seen from the results that the number 1500 paper or the 7 micron average grain size (close to the theoretical optimum) produced the highest voltage output.

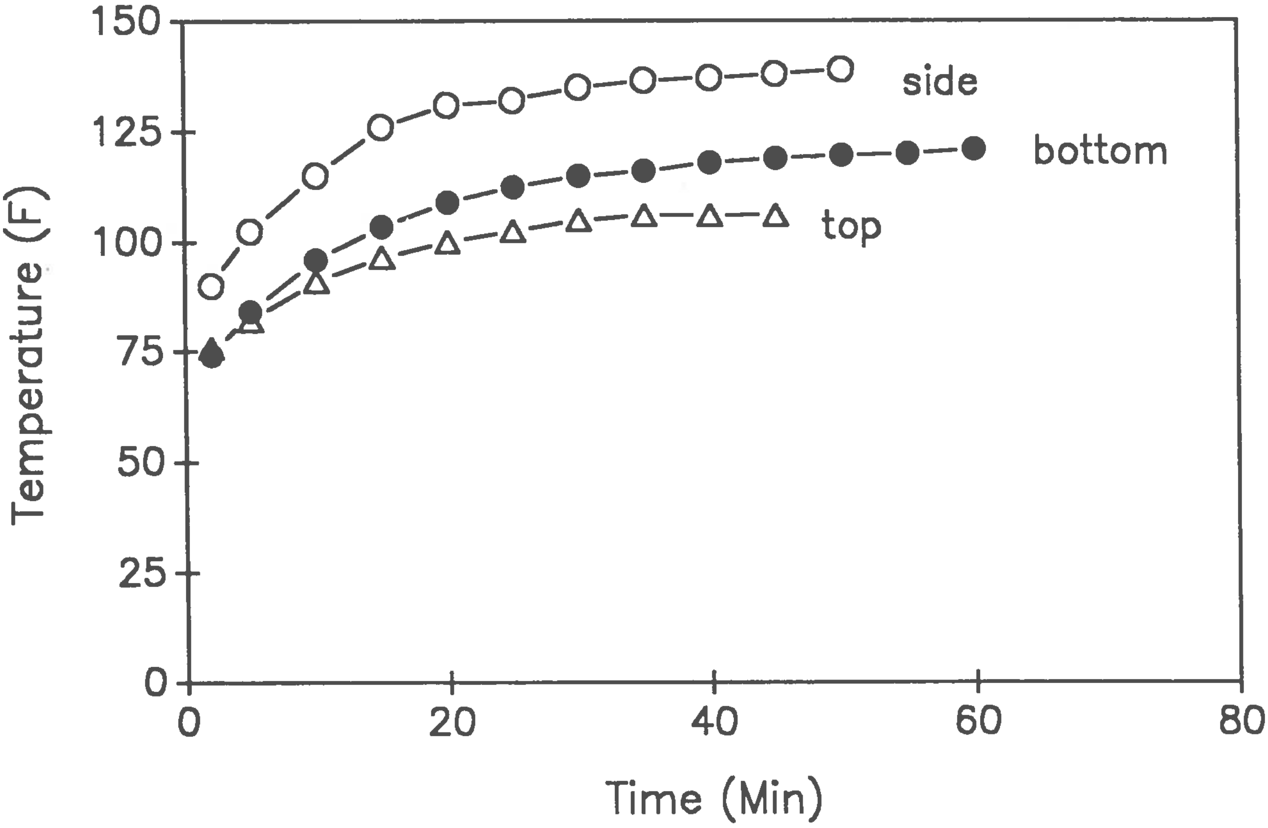


Figure 67. Temperature of Converter as a Function of Time

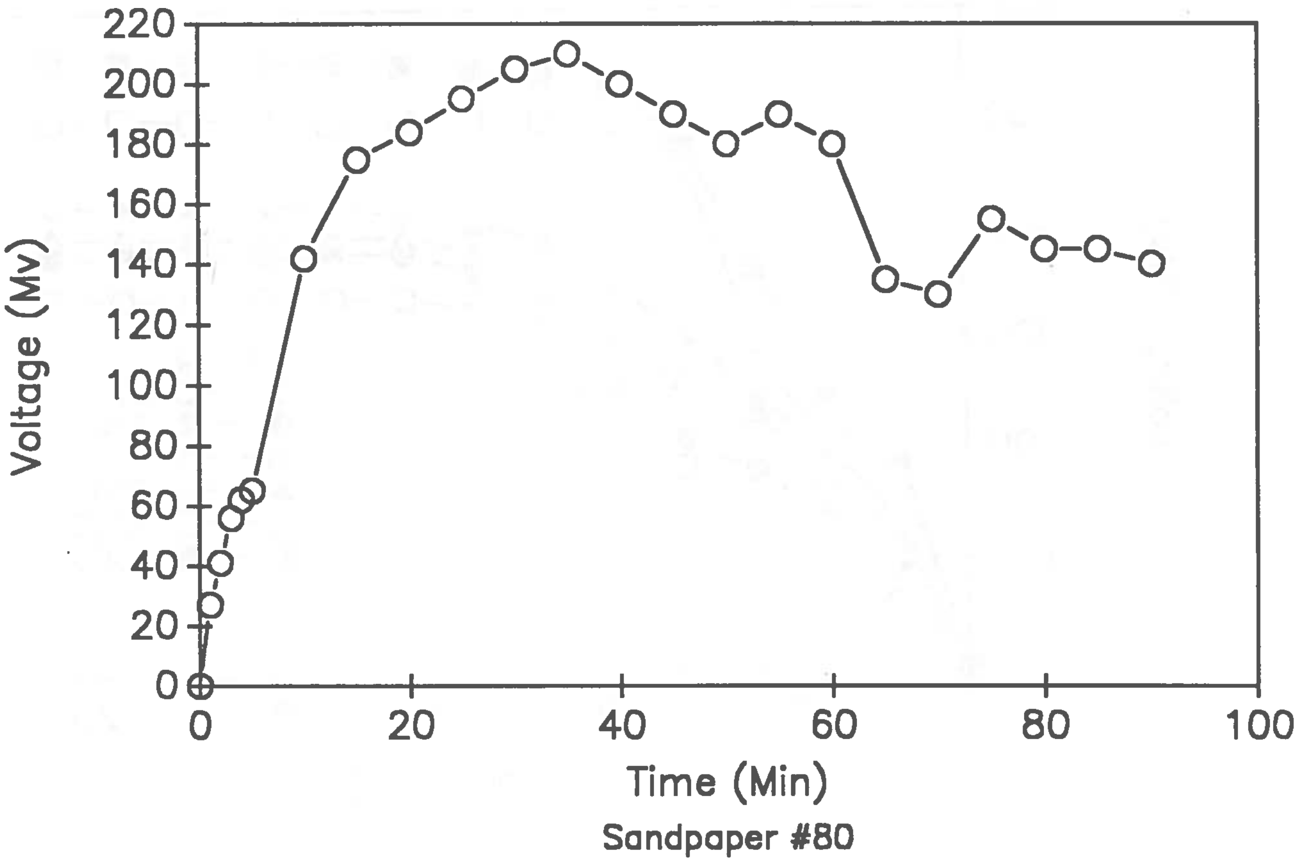


Figure 68. Open Circuit Voltage as a Function of Time

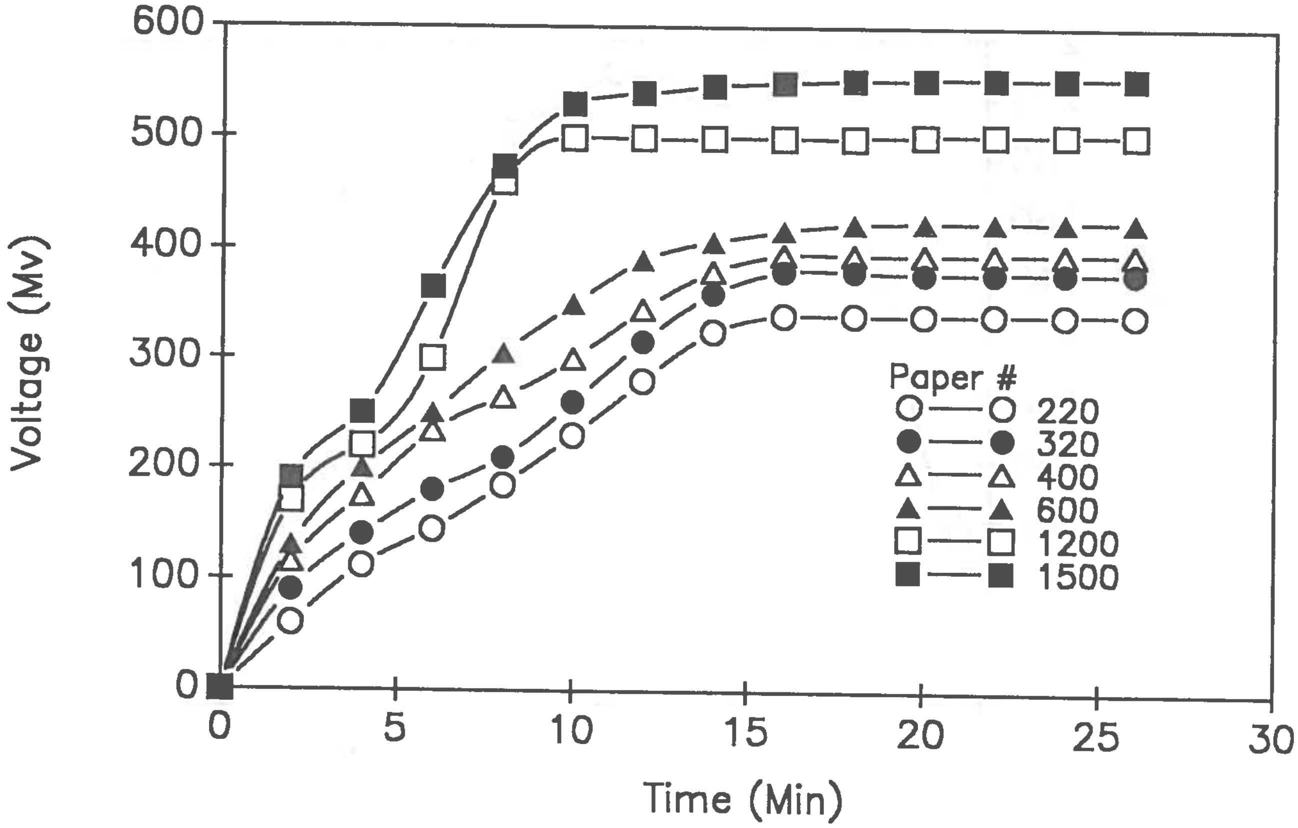


Figure 69. Open Circuit Voltage vs. Time for Various Size Grains

i. Short Circuit Current

The short circuit current (actually not quite short circuit since the instrumentation had some impedance) as it varies with time is presented in Figure 70.

It can again be seen that the current increases, reaches a maximum and then decreases to a steady level as time progresses.

j. The IV Diagram

One of the best methods of evaluating the Antenna Solar Energy To Electricity Converter (ASTEC), is to obtain the Current versus Voltage (IV) curves for different radiation intensities.

If the complete curve is obtained the maximum voltage (open circuit), the maximum current (short circuit), and the maximum power (The voltage and corresponding current value from the IV curve which give the largest product value) can be obtained easily. These three quantities are the most important information about the performance of this conversion device. See Figure 71.

The data and results presented here will be discussed in detail in the next section.

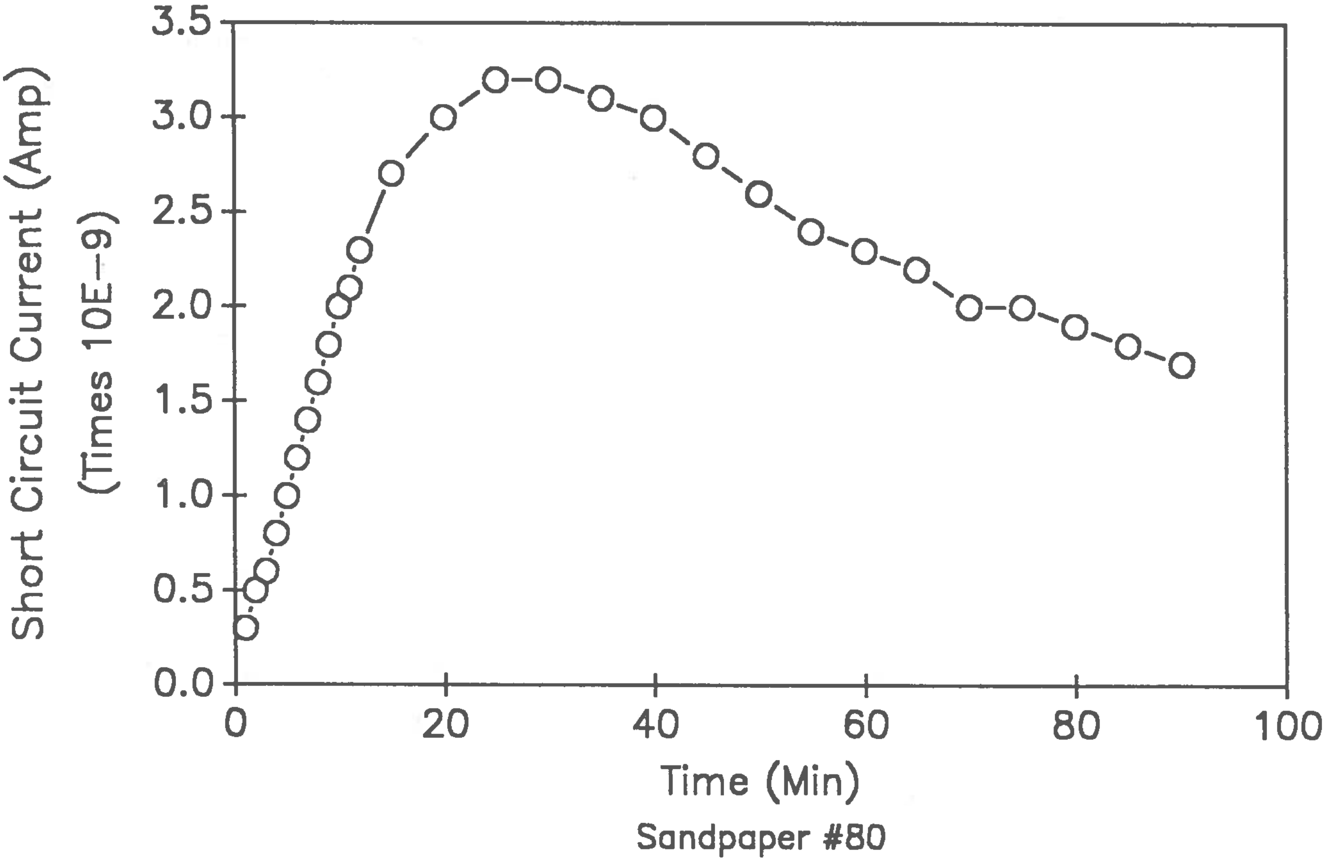


Figure 70. Short Circuit Current vs. Time

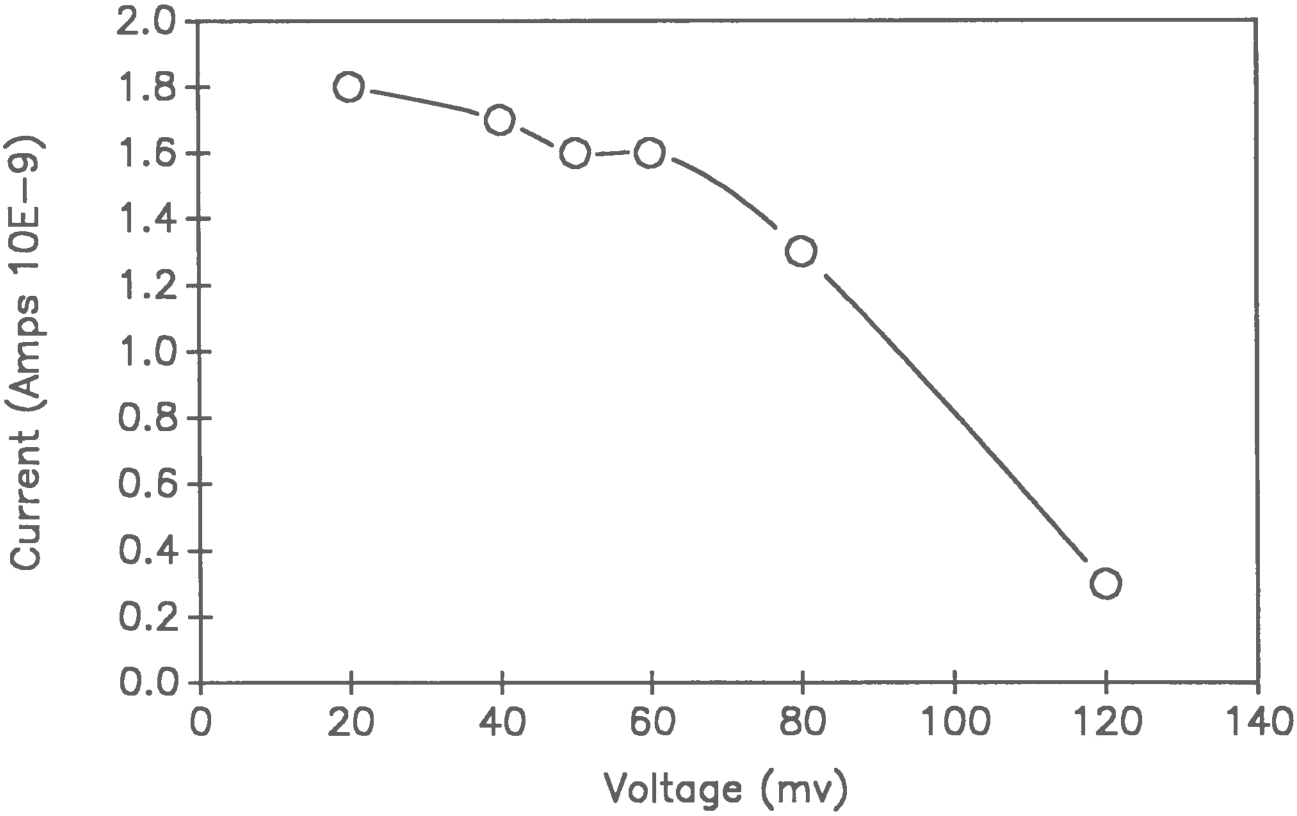


Figure 71. Current - Voltage (IV) Characteristic Curve

SECTION IV

OBSERVATIONS

The objective of the work performed under this contract was to show the feasibility of using antennae to convert electromagnetic wave energy to electricity at conversion efficiencies exceeding those obtained in solar energy-to-electricity conversion by solid-state devices.

As mentioned earlier the Solid-State Theory, shows that a certain amount of energy is required to remove an electron from the atom (usually referred to as the forbidden gap). This energy is different for each material with semiconductors having the most favorable range. The theory predicts that electromagnetic energy and, especially, solar energy can be converted to electricity with these devices.

As a function of the wavelength, the solar spectrum has quanta or energy bundles varying greatly in energy (the short wavelength quanta having much more energy than the long wavelength ones); therefore only one wavelength and its quanta can work at 100 percent conversion efficiency for a particular material. The quanta which have less than the required energy (less than the forbidden gap--or somewhat modified if the material has donor or acceptor impurities) cannot free electrons. Thus, this group of quanta and their energies are wasted. Their energy is converted to heat which is actually detrimental to the energy conversion efficiency. The quanta with energies exceeding the forbidden gap, will free electrons

but only the energy equal to the forbidden gap is used; the excess is again wasted, often with negative effects on the conversion efficiencies.

The Solar Energy and Energy Conversion Laboratory of the University of Florida has performed significant research in collecting and converting solar energy to other forms of energy. It was found that the absorption efficiency can be influenced greatly and thus, controlled by the geometry of the absorbing surfaces.

This work was started about 30 years ago and "selective surfaces" were developed. Since most of the energy used by man is in the form of heat, the conversion of solar energy to heat was the major effort pursued. It was, however, also considered that, if other forms of energy are needed, conversion directly into those forms should be possible. One of the major considerations was the direct conversion to electricity. It was thought that properly designed geometric shapes could, act as antennae and produce electricity.

Furthermore, nature seems to always convert solar energy into electricity with antennae, rather than with solid-state devices. Insects, which often communicate in the solar windows (the wavelength at which there is low solar activity), accomplish this feat with antennae.

Antenna theory allows the conversion of electromagnetic waves into electricity at up to 100 percent conversion efficiencies in contrast to solid-state theory, which allows a theoretical maximum (with a single device) of about 24 percent. Presently available solid-state converters for solar energy (solar cells) give about 10 percent conversion efficiencies with some specially selected ones up to 15 percent.

Adherence to a well-developed plan, promising a logical procedure was considered the best, most efficient, and most effective approach to prove the feasibility of antenna conversion devices, which promise to exceed greatly the conversion efficiencies obtained today by solid-state devices.

To make the investigation meaningful and straightforward, it was decided to divide the problem into several subparts: (1) the collection of the electromagnetic energy, (2) conversion, (3) coupling out of the energy, and (4) possible rectification, if desired.

To investigate the absorption, it was decided to start in the microwave range so that the sizes and geometric shapes would be large enough to be able to control and manufacture them to specifications. The actual frequencies used were dictated to some extent by the availability of equipment, microwave generators, and instrumentation. This choice allowed the investigation to be carried out at considerable reduction in expenditure, since expensive equipment did not have to be purchased.

The investigation was started with variable frequency generating equipment covering the range of 0.2 to 3.0 GHz, and associated instrumentation.

After thorough investigation and optimization in this range, an up to two order of magnitude reduction or miniaturization was accomplished by using 10 GHz fixed frequency generating equipment, and associated instrumentation.

After much experimentation in the 10 GHz range and obtaining the characteristic behavior for the most important parameters, the results from these investigations were used to arrive at the optimum geometries and configurations.

A few optimized configurations and arrays were built of paper and wax, and used with the 100 GHz equipment. This proves that the basic behavior of the electromagnetic wave to electricity converters does not change appreciably with wavelength if the elements are scaled properly.

At 100 GHz, the height or length of the elements is about 300 times that required for solar and light to electricity conversion.

The results indicate that the theoretical predictions are essentially correct.

After the microwave studies at 0.2 to 3.0 GHz, 10 GHz, and 100 GHz were completed, the study was extended to the solar and light range.

Having established the optimum design and configuration it is necessary to miniaturize those designs to apply the solar and light frequencies.

Many scientists, crystal growers, microelectronics experts, material science specialists and others, were consulted and none of them saw any great difficulties with the fabrication of the proposed antennae arrays. All the steps required for this have been carried out by these people but for other purposes, however these individual steps have never before been put together in this arrangement.

The fabrication would require crystal growing equipment, photolithographic facilities, microelectronic circuit manufacturing capabilities and other needed equipment. The alternative would be to go to these groups who have these capabilities, equipment, and facilities and have them manufacture the Antenna Solar Energy to Electricity Converters (ASETEC).

A. THEORETICAL ANALYSIS

Two basic theories had to be used to analyze the behavior of the electromagnetic wave to electricity converter. One was the theory governing the absorption of electromagnetic waves as a function of geometric configuration, while the other was the antenna theory, describing the conversion of the absorbed electromagnetic waves into electricity.

1. Absorption Theory

The first theory presented in this work was the one describing the absorption of electromagnetic waves (in contrast to the theory based upon quantum absorption) as influenced by geometry.

This report showed how much the absorptivity, reflectivity, and, where appropriate, transmissivity can be controlled by geometric configuration, allowing theoretically at least, almost 100 percent absorption of the energy falling upon the "textured" surface. The interesting, consequence is that the theory requires solid interception of the energy.

2. Antenna Theory

Since the purpose was to convert the electromagnetic energy, after absorbing it efficiently into electricity, this conversion is generally described by the antenna theory.

This theory is used to predict the geometry of the individual elements of an array to convert the incoming waves into electricity.

Most of the antennae used in applications are designed according to the theory developed for them. The theory applies mainly to metallic antenna elements, the type used in the field of communication. Nature uses dielectric materials to grow the antennae of insects. This investigation also revealed that the dielectric materials used for the construction of the antennae produced considerably better conversion efficiencies than their equivalent metallic counterpart.

Furthermore, the antenna theory was mainly developed for antenna configurations for single-frequency response. As a matter of fact, it is desirable to tune the antenna so that it will respond only to the frequency used, and attenuate other frequencies. The application of this theory results, therefore, in thin elements of definite dimensions related to the frequency to be absorbed. For maximum efficiency, definite spacing of the antennae elements is required.

This last requirement does not agree with the result obtained earlier from the absorption theory, the latter requiring solid absorbing surfaces with no spaces or holes in them. Also since they have to respond to a range of frequencies, or being broadband antennae, they must be thick. This latter design approaches the requirements of the wave absorption theory.

The number of results presented earlier for the 0.2 to 3.0 GHz range, 10 GHz, 100 GHz and, at the solar or light frequencies show that the wave absorption theory and antenna theory give design configurations, differing at the lower microwave frequencies but converging at 10 GHz and above into one and the same design.

B. EXPERIMENTAL INVESTIGATION

Because the purpose of the experimental investigation was verification of the theoretical predictions, the objective was to set up equipment quickly to establish the feasibility of converting electromagnetic waves into electricity, using the antenna principle, and accomplish this at conversion efficiencies considerably above those obtained in solar energy conversion with solid-state devices.

Again, as mentioned earlier, this was done in four steps or ranges:

1) 0.2 to 3.0 GHz
2) 10 GHz
3) 100 GHz
4) Solar and Light Frequencies

Each subsequent step utilized the findings of the previous ones, thus, the experimental work followed a logical and well-thought-out plan. It was to take the original concept and, through verification, establish it as fact.

1. 0.2 to 3.0 GHz

To reduce the cost of this investigation available equipment was repaired and put into service. This equipment determined the range of frequencies for the investigations. The exact frequencies are not important as long as one can start out with reasonable sizes, then minaturize the configurations in order-of-magnitude jumps to arrive at the final desired arrays.

First a microwave generator was used with a modified dipole antenna transmitting a beam of microwave energy at frequencies between 0.2 and 3.0 GHz, one frequency at a time.

A receiving antenna, also of the modified dipole design, was used to receive the energy and convert it to electricity. Part of this converted energy was sent to a spectrum analyzer with a display unit to determine the frequency and wave characteristics of the transmitted power. Most of the electricity produced was, however, rectified and used to drive a small electric motor. The rectification, although not very efficient, was necessary since no high frequency AC motors were available. This was done to demonstrate the feasibility of efficient wireless power transmision.

The beam energy was determined by measuring the temperature changes of a beaker of water caused by irradiation with the microwaves. The beam energy determination was made under transient conditions when the temperature of the water was the same as the ambient air temperature, and under steady-state conditions, after an equilibrium water temperature was established. Both measurements gave the same results.

Field intensity and power meters, on order at the time, were used later to substantiate the results obtained with the water beaker.

The losses and the expected conversion efficiencies of the conversion system were analyzed as follows:

The microwave generator, operating at 75 percent efficiency in the final stage with a 15-watt Klystron power tube, produced 11.25 watts. At a coupling efficiency of 60 percent the output at this stage was 6.75 watts. The transmission line, with an antenna coupling efficiency of 90 percent, gave 6.08 watts delivered to the antenna. With an antenna efficiency of 90 percent, the total energy radiated was 5.47

watts. With the polar radiation pattern having a divergence angle of 30 degrees total and only one-half of the energy radiated into the direction of the receiving antenna, 0.33 watts were intercepted by the receiving antenna.

The DC electric motor was calibrated for its power requirement as a function of rpm. Operating under the above conditions, the motor operating at 420 rpm required an input of 0.23 watts. Since there was a loss in the coupling of the output transmission line with the receiving antenna and then the losses in the Schottky Barrier Diode Bridge (full-wave rectifier) the final output was 0.23 watts. The efficiency of conversion (even with transmission line, coupling, as-well-as rectification losses) was 70 percent for the receiving system. Thus the efficiency of the electromagnetic wave-to-electricity converter actually was even higher.

These results were encouraging and seemed to establish the theoretical prediction that conversion efficiencies considerably in excess of the 10 to 15 percent obtained by solar cells (solid-state devices) should be possible with antenna conversion.

Subsequent experiments using the Power Density instrumentation and Power Meter substantiated the results. Much more data were taken and polar diagrams or plots determined for a number of different antenna element designs.

One such plot, presented in Figure 44, shows the receiving pattern of a broadband dipole (D), a conical helix (C), a metal cone (B), and a metal pyramid (A). The respective power conversion efficiencies of the receiving system are plotted in this polar diagram at a beam power frequency of 0.35 GHz. The pyramid produced the highest conversion efficiencies. This configuration best meets the

absorption theory requirement of close spacing because pyramids can be placed close together with no lost space between them.

The cones were a close second in the conversion efficiency, almost as good as the pyramid. Most natural structures used as antenna converters are conical.

Even though the antennae were designed as broadband antennae they exhibited the best response at the frequencies which fit their theoretical dimensions. The overall power transmitted is shown in Figure 45. The actual response is much more uniform or flatter than presented here, since the transmitting antenna also exhibited the same response and the beam power was reduced at the higher frequencies, thus keeping the relative relation of conversion more uniform.

Different spacing was investigated when the individual elements were combined into arrays. Again, the combined effect of antenna converter, transmission line and rectification was determined, showing spacing closer than predicted by antenna theory, but not as close as that predicted by absorption theory. Produced the highest conversion system efficiency (Figure 46).

Since it was desirable to investigate each effect separately, it was decided to use the antenna only as a waveguide and determine its power beam amplification factor as a function of geometry, not coupling energy out and having to include the coupling efficiency.

In a study of the antennae used by nature, the rods and cones in the eye, the insect antennae, etc., it was observed that rather high length-to-diameter ratios were characteristic with the length in the range of about 10 power

beam wavelengths. Since constructing of such large L/D models would not have been practical, in the 0.2 to 3.0 GHz range a 10 GHz experimental setup was used.

2. 10 GHz Range

The 10 GHz generator was set up as shown in Figure 47 with the beam strength analyzer located on the beam axis. The distances between the two components varied from 2 to 6 feet during the experimentation.

The ASETEC element was then located in the beam to produce maximum amplification. To accomplish this the axial position and the radial positions were adjusted.

Different geometric configurations were investigated including some of the insect antenna models shown in Figure 48. They were made of paper coated with beeswax, to simulate nature as closely as possible.

For the purposes of developing the ASETEC the previously optimized shapes were used, rods, cones and pyramids of various diameters or base deminsions and various lengthz They were made both of metals and dielectrics but most of the time the dielectric materials where used. Some of the elements are shown in Figures 33, 34, 35 and mounted for evaluation in 49.

a. Directional Characteristics (Polar Diagrams)

After the apparatus was set up as shown in Figure 47, the amplification factor was determined. The amplification factor (AF) is defined as the beam strength measured with the element between the generator and the beam strength meter, divided by the beam strength without the element.

As the axis of the ASETEC element was slowly rotated with respect to the beam axis from 0 through 360 degrees the amplification factors were recorded. When plotted on a polar diagram they produced the typical plot as shown in Figure 50.

The amplification factor, of the configurations tested at 10 GHz, was largest for the axes of the elements or arrays parallel with the radiation beam. After a length to base ratio of about 10 the amplification factor for angles closer to the perpendicular position decreased making the polar diagrams longer but thinner. This again agrees with the theory.

If the radiation arrives from all angles, as it will with the sun as the source, the area of the polar diagram is proportional to the total amplification or power output of the element or array. The maximum area value occurred at a length over base ratio of about ten. Again, this ratio is similar to the values of nature's converters such as the rod and cones in the eye, or insect antenna which are not intended to be directional.

Figure 51 presents the results of truncated cones made of paper and beeswax and compares one element with arrays of three elements with different spacing between the elements.

b. Length over Base Ratio

With the axes of the ASETEC model element parallel to the beam the effect of the length over base ratio as it effects the amplification factor, is given in Figure 53. It shows that the directional characteristics become more pronounced as the length of the element increases. With the configurations evaluated, amplification factors of over eight were obtained.

However, when the radiation is more diffuse so that radiation is received from all direction (not necessarily at the same intensity) a maximum amplification factor (a combination of all the directional values) is obtained at a length over base ratio of about 10.

c. Axial Position of Element or Array

Since most of the experimentation was carried out in the near field of the electromagnetic wave generator (microwave generator) some variation of the amplification factor with movement along the energy beam axis was predicted and also observed.

Maximum and minimum values for the amplification factor were found when the element was moved through one wavelength. In the 10 GHz set of experiments that distance was 3 centimeters.

For the experimental results reported here, enough movement was used to obtain the maximum value which was then recorded in each case. The actual experimental curve showed the typical M shape obtained in all cases. Figure 54 presents two of these typical curves for a metallic and a dielectric element of the same configuration.

The Amplification Factors in this case have not been optimized since the effects of the L/B ratio effect was intended to be investigated.

d. ASETEC Materials (Metals and Dielectrics)

Most antennae in engineering applications are made of metals, while the antennae used by nature are constructed, or actually grown, of dielectric materials.

In this investigation both metals and dielectric materials were used. The metals were copper and galvanized plates and the dielectric materials were plexiglass and paper covered with beeswax.

At the low frequencies of the microwaves used in this investigation the metal elements performed about the same as the dielectric elements of the same configuration. At the higher microwave frequencies however, the dielectric materials of proper thickness performed considerably better than their metallic counterparts. Figure 54, which was used to show the effects of axial movement can also show the difference in performance of the dielectric and the metallic antenna. This same basic behavior was found with all different configurations in the 10 GHz range. The dielectric configurations always out performed the metallic ones.

e. Wall Thickness of ASETEC Elements

The wall thickness of the antenna elements had considerable influence upon the performance as expressed by the amplification factor.

Plain paper configurations did not give much amplification. However, when they were coated with wax they amplified the beam intensity. The thickness of the coating, or wall thickness, further increased the amplification. Solid dielectric configurations did not perform well. See Figure 55.

f. Spacing between Antenna Elements

From the antenna theory, a definite spacing of the elements is required for maximum conversion efficiency. This, however, does not seem to agree with actual array designs. If

an array is designed properly it should give one hundred percent conversion efficiency and therefore, no radiation is able to penetrate it. In practice, however, arrays are stacked, one behind the other so that the second picks up what the first missed and the third what the first two missed and so on.

The absorption theory on the other hand requires that the interceptor form a solid surface with no holes or spaces which would allow energy to penetrate. This seems to indicate that the required design is different, depending upon which theory is used as basis.

The theories usually are applied to narrow band (preferably single frequency) antennae of simple design such as dipoles. When arrays are used it is usually stated that the interactions of the elements become too complicated to be expressed well theoretically; experimental evaluation is the quickest and the best.

The broadband antennae used here differed in design, depending upon which theory was used as the basis for optimization at the lower range of the microwave frequencies used, 0.2 to 3.0 GHz. The difference was not as great as predicted by theory. The maximum performance was obtained at spacing closer than that predicted by the antenna theory. At 10 GHz, the difference for the optimum design vanished and the close spacing of the pyramidic elements proved to be best.

Since the closest spacing was found to be best, pyramids work better than conical configurations since round objects leave open spaces or holes even when they touch.

Figure 56 gives the results in terms of the amplification factor for different spacings in terms of wavelength, showing that the optimum design requires close

spacing forming the solid barrier required by the absorption theory as the interceptor.

g. Number of Element in the Arrays

Theory indicates that when the number of antenna elements is increased the performance or output increases. Naturally, this is based upon proper interconnection of the elements and eliminating as much as possible wave interference.

Again the experimental work substantiated the theoretical predictions. Some work was done with single elements to form a basis, then a dipole arrangement (the classic antenna) was used. Beyond the two-element array, a three-element arrangement was used as the basis for the multiple-element arrays. A three-element arrangement can be expanded indefinitely by adding elements in the same pattern. In this manner arrays could be produced that can cover any desired surface area, thereby being able to intercept any desired quantity of energy and convert it to electricity.

Figure 57 presents the results of some experiments, giving the data for 1, 2, 3, 6, 9 and 16 element arrays. It shows that the amplification factor increases, but at a decelerating rate. Thus, for multiple arrays it should reach a constant value when enough individual elements are used.

h. Coupling to the Antenna Elements

Having established the optimum element configuration for amplification it becomes necessary to couple out the energy from the element or waveguide. This is done with probes of various materials and designs and inserted to or attached at different locations.

Metallic probes were used in most of the work since they are the easiest to use and most convenient. However, a good impedance match between the dielectric element and the metallic probe is difficult to accomplish.

(1) Types of Probes

Many different types of probes were used. Designs of metallic configurations such as rods, arrow heads, inverted arrow heads, Tee shaped probes, three-pronged or multi pronged probes, disk-shaped probes, etc., were all used, see Figure 58. The three-prong and disk probes proved to give the best coupling with dielectric to metallic match.

In addition to the metallic probes, dielectric probes made from solid materials were used to give a better impedance match with the antenna element. Eventually, this dielectric still had to be coupled to a metallic transmission line with an imperfect match.

Some of the antenna elements were filled with water, doped with salts and a plastic tube attached to the element and filled with the same solution. In this manner, a very good impedance match was obtained, however, resulting in a much less convenient physical arrangement.

For the above reasons the metallic probes were used in most of the work and the results reported here. Figure 59 gives a relative comparison of the performance of a number of the probes used.

(2) Position of the Probes in the Elements

The probes used to couple the energy out of the antenna element of waveguide can be of many different

designs as discussed above and then positioned and or attached to the antenna element in many different arrangements.

Theory predicts that the probe should be positioned or attached at the maximum current point. This point would be about one quarter of the element length from the point for the pyramid. The voltage coupled out was good when the probe was at the theoretically required position but it was found to be even better when the probe was even with the base located on the axis of the element. Figure 60 gives the performance as a function of the probe position.

The base position of the probe agrees also with the probe position nature uses in its design of insect antennae: See Figure 5. The output voltage actually drops to a minimum as the probe is moved along the axis of the element from the tip to the base from the one quarter point and then rises to the highest value when at the base.

The above discussion shows that the extensive work with the 10 GHz microwave equipment established the optimum configuration and established the basic behavior as a function of the most important parameters. This work also leads to a much better understanding of the electromagnetic wave to electricity conversion process and phenomena.

3. 100 GHz Range

Theory predicts that there should be no appreciable change in performance with frequency on wavelength if the scaling is done properly. Spot checks of the effects of the main parameters upon performance were then carried out.

The energy in the generated beam was considerably less, therefore,the measurements were much more delicate than

those at 10 GHz. Any movement of the body while carrying out the experiments changed the readings. Stray fields had to be eliminated. Even with 10 GHz it was necessary to perform some of the experiments in a Faraday cage. With the 100 GHz equipment this became even more important.

If one stood in the same place and position while taking the data consistent and reproducible results were obtained. However, if one shifted positioning, the absolute values of the readings changed, but their relative relationship remained the same.

Because of the great care needed to carry on the experimentation, the multitude of experiments done with 10 GHz were not repeated. Only the optimized array configurations were used and spot checks were made to see if their behavior is the same as that found at 10 GHz. The behavior at 100 GHz was essentially the same as that at 10 GHz with the antenna elements and arrays properly scaled for the smaller wavelength of 3 millimeters.

The amplification factor with the element or array axis oriented at different angles to the beam axis produced points on a polar plot within a 10 percent band, 5 percent on either side of the polar plot of 10 GHz.

Only the optimized length over base ratio was used to double-check the results; again the results fell within a few percent of the values obtained with the 10 GHz equipment.

With a wavelength of only 3 millimeters the position for maximum output was very critical. A very small movement along the beam axis produced a change in the result. The curve obtained again using the maximum values, had the same characteristic M shape as those obtained with 10 GHz.

Paper elements coated with wax and one metal element were used at 100 GHz. The dielectrics were used as single element and in two by two arrays. The metal was used only as a single pyramid. Again the difference between dielectrics and metals was about the same as at 10 GHz.

Only one wax coat was put on the paper configurations which seemed to be close to 0.3 millimeters in thickness to correspond to correct scaling. The coating could not be applied perfectly uniform and was somewhat uneven. This did not seem to be a critical factor, a fact also observed in the 10 GHz range. Nature does not produce perfect shapes in insect antennae and they have their irregularities and bumps on them but seem to perform about equally.

Only close spacing, the elements actually touching, was used at 100 GHz, which was shown to be optimum at 10 GHz, and close to it in the 0.2 to 3.0 GHz range.

The number of elements in the 2 by 2 array produced about fours time the amplification obtained with one element. This is close to the result obtained with 10 GHz.

For coupling the energy out of the dielectric elements only the rod probe was used. Because of the small size of the elements (only about 300 times larger than the size required for solar conversion) it was difficult, time-consuming, and expensive to accurately manufacture the various other probes. The relative behavior really did not change; only the absolute output would have been greater with the optimum combination.

As far as probe position is concerned, again only the base position, which produced the maximum output with 10 GHz, was used with 100 GHz.

Enough of the 100 GHz work was carried out to convince the experimenters that the behavior does not change noticeably. This one order of magnitude change in wavelength, thus again substantiated the theoretically predicted results.

Having established that the performance is essentially independent of wavelength, being thus the same if the antenna elements and arrays are scaled properly for a particular wavelength or frequency, it was decided to carry the experimental work into the solar and light range.

4. Solar and Light Range

To obtain results and characteristic behavior in the solar and light range, with the limited funds, the principal investigator came up with the idea of using Silicon Carbide (SiC) which is commercially used in Carborundum® paper. SiC has tetrahedral crystals which are grown, then crushed to different size chips, mixed with a binder and then applied to a paper as backing.

It was thought that if the paper backing is carefully removed by scraping, and collector wires applied to both the top and bottom, enough of the crystal chips should be lined up properly, even though the total is randomly arranged, so that when this system is exposed to sunshine or light it should produce electricity.

A simple system was quickly assembled to show if this arrangement could be used to obtain the desired experimental information.

A piece of number 80 Carborundum® paper (having an average grain size of about 0.4 mm) was carefully prepared by scraping the backing paper off the SiC layer. The insulation

was stripped off the end of a fine stranded wire cable for about one inch and the exposed wire strands fanned out. Two of these wires were prepared, then one of the fanned ends was placed on top of the SiC layer and the other on the under side where the paper had been scraped away. A glass cover was put over the system and a piece of plywood was placed underneath. The whole system was held together by a welding clamp. The dimensions of this arrangement were about 3 by 3 inches, with the specially prepared section in the center having a diameter of about 1 inch.

The system described above was exposed to light and, as expected, electricity was produced: and the output measured in millivolts. Then the experiment was then taken outside and sunshine was used as the source. Again, the solar radiation was converted into electricity.

Having established that this arrangement, using Carborundum® paper with its randomly orientated chips, works well enough for experimental analysis of the most important parameters for the Antenna Solar Energy to Electricity Converter, more elaborate, careful, and accurate experimentation was planned and carried out.

This method was used to evaluate the basic characteristics of the ASETEC systems at relatively low cost and with simple systems. Since Carborundum® paper is available for many element or grain sizes, the data and results of the experimental evaluation cover a wide range.

The difference between the results presented here, obtained with the simple and inexpensive systems, and properly and carefully designed and manufactured arrays is that the correctly designed systems would give considerably higher conversion efficiencies. The latter's characteristic behavior, however, would be expected to be the same.

Again the analysis of the basic behavior as a function of the most important parameters will follow the work of the microwave studies. Some of the parameters presented here are naturally a result of the methods used in making the every day, commercial Carborundum® paper.

a. Directional Characteristics

The experimental work carried out with the Carborundum® paper obviously correspond generally to arrays since the collector grids touched many elements.

As the ASETEC system was oriented at different angles to the wave energy beam the typical pearshaped curve, also obtained with the microwave energy beams, was obtained. This is due to the geometry which makes textured surfaces less directional than the flat surfaces which generally follow the cosine law. More energy is trapped and thus converted at beam angles other than the normal to the array since the waves hit the elements at much more favorable angles than they would a flat surface. Another factor contributing to this is that, because the grains or chips which form the antenna elements are randomly oriented, some of them are actually favorably oriented when the beam comes in at a different angle.

The pear-shaped curve was slightly more squashed than those obtained with the microwave experiments caused by the random arrangement, a factor which the properly designed arrays do not have.

b. Grain Size

A series of different numbered Carborundum® papers were obtained. They were the regular commercially available grades which can be purchased in any hardware store.

The grain sizes for the purpose of these experiments were determined by analyzing each paper under the microscope, then taking the average value. A certain area of the Carborundum® paper was taken and all the grains analyzed in that area, making this analysis a tedious and time-consuming task.

The Carborundum® papers used in this investigation and for which results are presented below.

Number	Grain Size	Number	Grain Size
60	0.50 mm	400	0.02
80	0.40	500	0.014
100	0.30	600	0.012
220	0.15	1200	0.010
320	0.05	1500	0.007

The Number 1500 paper gives just about the right size elements or grains needed for the solar energy to electricity conversion.

When individual chips or crystals were contacted by cat whiskers, touching the crystal in its optimum orientation, the maximum open circuit voltages were obtained. When collector wires were used, the values were lower since some of the crystals, not properly oriented, reduced the total output. When a single strand was used the values were higher than those from a grid collector configuration. This characteristic was due to the random orientation of the Carborundum® paper grains and many of the grains worked against each other. When cat whiskers were used to find the single crystals the search was carried on until the maximum

voltage value was obtained. Again, this was tedious and time-consuming and actually only possible with the larger grain sizes.

As shown in the microwave studies where the sizes and configuration were optimized, with light or solar energy the Number 1500 paper produced the highest voltages.

Figure 61 gives the output voltage for a fixed size collector configuration, contacting fewer grains when they are large and a very great number when they are small. Voltages of over 600 millivolts were generated with the experiments carried out under moderate illumination.

The size distribution of the grains which was typical for all the papers is shown for the number 80 paper in Figure 62. The distribution curve is quite symmetrical around the average value, which had the greatest number of grains. The distribution curve is relatively narrow.

c. Collector Spacing

The collectors which contact the grains or individual crystals and collect the electrons have an optimum configuration for maximum performance. If there are no collectors, then there is not output. When the metallic collectors form a solid shield, the radiation cannot reach the converter elements and, again, the output is zero. In between these two extremes there must lie a maximum value for most efficient collection.

Figure 63 presents the data around this maximum point which occurred with the configurations evaluated under this project at about 10 collectors per inch, forming a screen.

If transparent or translucent materials were used for the collectors, such as a thin layer of tin oxide the collector spacing would be zero or providing continuous contact and with properly arranged arrays the output should be a maximum.

d. Solar or Light Intensity

Solar energy was only used to prove that the conversion process is essentially the same as that when an incandescent light source is used. It is so much simpler to carry out the experimentation in the laboratory under controlled and steady state conditions.

First a single AC-powered incandescent light source, a spotlight, was used. It was found that the electromagnetic fields generated by the leads and source itself interfered with the instrumentation measuring the output. This problem was solved when a DC source, a 12-volt automobile battery was substituted, powering an automobile headlight.

It was noticed, however, that the light intensity with a single light source was far from uniform across the sample, so, later arrays of light sources were used, given a much more uniform light intensity across the test sample.

The light sources were found so much more convenient than using the sun as the source since the experiments could be carried out in the laboratory under steady state conditions with the energy source constant and stationary.

The light intensity or radiation intensity falling upon the target was varied by changing the distance between the source and the target.

Figure 64 shows that the converter output increases with irradiation intensity. However, the effect is not linear since other things such as heating of the sample etc., accompany the increase in intensity. Also, physical changes may occur if the temperature becomes high enough to soften the binder.

The variation is, however, close to what the theory predicts. It would follow the inverse square law if the source were a sphere, radiating equally in all directions. With spotlight sources, or sealbeam headlights which are directional, the pattern is different but still the beam spreads out over larger areas as the distance from the source increases.

e. Contact Pressure

When the contact pressure of the collector grid with the Carborundum® layer was light, the output was low, but increased as the pressure of the contact increased.

Figure 65 presents this variation in output as a function of the pressure. At light pressures (measured here as turns of the wing nuts of the screws pressing the collectors against the Carborundum® layers), it is low and increases to a maximum value at a critical contact pressure, after which it remains constant.

This last observation indicates that a minimum contact pressure must be maintained in the final designs for good and consistent output.

In the experiments carried out with the Carborundum® papers, far from ideal converters, at higher

irradiation intensities the binder softened and the crystals rearranged themselves changing the output with time. This phenomenon would not occur if a properly designed and manufactured array were used.

f. Impedance Matching

During the experimentation it was noticed that the output of a particular array varied considerably with the impedances of the loads and instrumentation (Figure 66).

So by changing the load impedance, the output could be made to increase when the matching of load to converter was improved. This fact is well known in electrical applications and was also born out here.

For some of the low radiation intensities and therefore very small outputs, the instrumentation alone put a considerably load on the system so that no truly open circuit voltages were obtained. High resistances were manufactured in the laboratory, often using paper or cardboard layers with alligator clips spaced at different distances. The paper, often several layers thick, or cardboard formed the resistance. In the air-conditioned and environmentally controlled laboratory, these values were consistent and constant, however if the humidity were to change the resistances of the paper or cardboard would also change. In those cases, it was only necessary to measure the load resistance before the start of any experiment.

g. Temperature Effects

With the microwave experiments no temperature effects were encountered because the configurations used as converters were fixed, optimized, and made of materials not altered by temperature.

With the Carborundum® paper, however, the binder holding the individual grains together softened, especially at higher irradiation intensities due to the increase in temperature, and then the grains which were under the pressure of the collectors rearranged themselves, naturally changing the readings.

For the above reasons data were taken showing how various quantities change with time.

Since the variations observed were all a function of the temperature a temperature time graph is presented in Figure 67.

The variation of other parameters are not a simple function of the temperature since, when the binder softens and allows the grains to reorient themselves, this reorientation continues even though the temperature remains constant from that point on. The degree of softening naturally controls the speed with which this reorientation occurs.

When the grains have reached their most stable orientation, under the pressure exerted upon them, no further reorientation will occur even though the temperature may be increased.

The changes in the orientation with time of the individual grains were also observed and followed in the microscopic analyses.

Figure 67 presents the temperature variations at three different locations on the converter, top, side, and bottom.

h. Voltage Output Variation with Exposure Time

The variation of voltage with exposure time was typical for the intensities of radiation encountered with solar energy as the source. The experiments were carried out in the laboratory where environmental conditions were constant. If the experiments had been carried on outdoors, the temperature, humidity, type of radiation (ratio of direct to diffuse), wind velocity and direction, etc., all would have affected the actual results.

However, under the constant environmental conditions the voltage output increased, reaching a maximum and then decreased somewhat, reaching a steady value with no further variations with time.

As mentioned before, this behavior can be correlated with temperature but is not a simple relationship since it is basically a function of the viscosity of the binder, which in turn is temperature-dependent in a complicated way.

Figure 68 exhibits this typical behavior, described above and observed in all cases, of tests with the Carborundum® papers. The typical shape of the curve can be either compressed in time or expended depending upon the intensity of the radiation.

i. Output Voltage as Effected by Grain Size

The output voltage is a function of the grain size and the closer the size comes to the optimum for a particular wavelength or band of the radiation source the large will be the output.

Figure 69 presents the voltage curves as a function of time for different grain sizes of Carborundum® paper.

As the grains became smaller and closer to the optimum size, the open-circuit voltage output increases. This is the result discussed earlier and shown here. As the grains form a better arrangement due to reorientation the performance of the total configuration increases.

Since the performance improves with time and reorientation because of the softening of the binder, this fact can possibly be used in the manufacture of better systems of this type through prolonged heating of the ASETEC systems.

The voltages presented in Figure 68 are not truly open-circuit voltages, since the instrumentation is putting a small load upon the converter, but they are close to it.

j. Short Circuit Current

The short circuit (again not quite short circuit since there is some impedance in the circuit) current when measured against time through the instrumentation impedance, is presented in Figure 70.

The curve is again typical in that the current increases to a maximum value then slowly drops off and eventually reaches a steady value.

The actual current values depend upon the degree of irradiation (which because of temperature changes) have the typical shapes compressed or expanded in time. These values also obviously depend upon the size of the converter since, the more the energy which falls upon it, the larger the amounts converted, resulting in larger current values.

k. The IV (Current versus Voltage) Diagram

Probably the single most useful diagram presenting the performances of an Antenna Solar Energy in Electricity Conversion (ASETEC) is the IV (Current versus Voltage Diagram).

A portion of this curve is given in Figure 71. A family of such curves is obtained one for each intensity of radiation, presenting the overall behavior of the ASETEC.

When the family of curves is determined, for a particular irradiation the maximum current, the maximum voltage and the maximum power which the device can produce, can be read right off the graphs.

The maximum current or short-circuit current occurs when the voltage is zero thus, it is at the intersection of the curve with the Y axis. The maximum power occurs at the point of the curve when the product of current times voltage produces the largest value, or when the rectangle under the curve formed by the I and V values is found which has the largest area. The point on the curve where the corner of this rectangle touches the curve, both the current and voltage can be read which produce this maximum power.

Now, from these curves the three most important results can be determined from the following curves:

1. Maximum Currents
2. Maximum Voltages
3. Maximum Powers

The main objective of this work, up to this point, was to demonstrate the feasibility of converting solar energy

to electricity by an antenna system and do this more efficiently than can be done with solid-state devices.

The data presented here with the discussion have shown that the conversion of electromagnetic waves to electricity is feasible, that the conversion efficiencies are much higher than those obtainable with solid-state devices, and it presents the basic characteristics of these devices in terms of the most important parameters.

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SECTION V

CONCLUSIONS

Based upon the work conducted here the following conclusions can be drawn:

1. It has been shown that electromagnetic waves can be converted efficiently to electricity by antenna arrays.

2. The conversion efficiencies at the microwave frequencies of 0.2 to 3 GHZ are considerably higher than what solid state devices can do in the solar range.

3. Going to higher frequencies and shorter wavelength does not seem to change the basic conversion characteristics.

4. The optimum designs as predicted by the absorption theory and antenna theory respectively approach each other as the frequency increases, becoming almost identical at 10 GHZ.

5. Work with light and solar energy on readily available and inexpensive arrays, (however far from optimum) such as Carborundum® Paper indicates that the conversion takes place as predicted but with only relatively few properly oriented elements taking part.

6. Elements of the right size and of the right materials have been grown by others, indicating that the technology needed for this work has already been developed.

7. Making the interconnections between elements requires techniques which exist presently in microelectronics. Thus this technology already exists.

8. All indications are that using pyramidic crystals of a dielectric substance, arranged with axes parallel, with a base of about 1 wavelength of the midband, and about 10 wavelength high, interconnected in the standard antenna array configuration have the potential of giving solar to electricity conversion efficiencies much larger than those obtainable with presently available systems.

9. Some of the findings which resulted from this work may also be important for applications in wireless power transmission, emergency lighting, developing of "perfect absorbing surfaces," thus, nondetectable by radar, etc.

SECTION VI

RECOMMENDATIONS

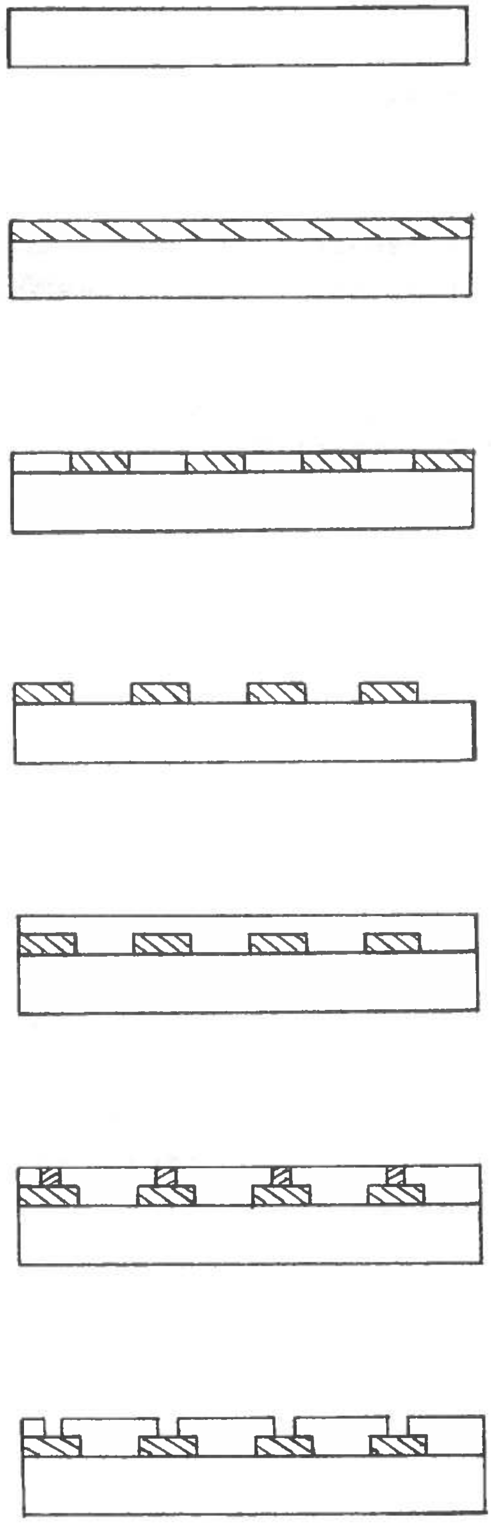
The next step in this research is the manufacture and evaluation of the conversion arrays comprising the main objective of the proposed work.

To carry out the above tasks, which, based on the previous work, should be pyramids, approximately 1 micrometer on the side, about 10 micrometers high, made of dielectric materials, closely spaced, possibly hollow, with disc probes at the center of the base about 1/4 micron in diameter, using, to start with, metallic probes and transmission lines, but later for better impedance matching dielectric materials (solids, liquids, etc.).

The manufacture of these arrays to be studied will require the help and support of personnel with experience in crystal-growing (vapor deposition, sputtering, sintering, etc.), microcircuitry, and photolithography as well as people who are familiar with the basic characteristics of the materials used, electronics-thin film experts to evaluate and improve the desired behavior, and to produce the efficient high frequency rectification when needed.

It seems that many of the procedures and tasks needed in this work have already been performed individually and for different purposes. Now these processes must be combined to give the desired results.

A possible procedure for manufacturing these ASETEC Spot Matrix Arrays (Figure 72) could be described as follows:



1. Support (insulator)

2. Photosensitive material (coating)

3. Light exposure

4. After development

5. Photosensitive dielectric (coating)

6. Light exposure

7. After development

July 20, 1987

Dr. Erich A. Farber
Department of Mechanical Engineering
University of Florida
Gainesville, FL 32611

Dear Professor Farber:

I would like to request references or papers pertaining to your work developing antennae for visible light.

I was quite thrilled by the short article in Advanced Materials and Processes (7/1987) on your work. Your small pyramidal antennae for visible light are very interesting from the materials development and processing viewpoint. The antennae are also interesting to me because I have some pet ideas (outside of the energy production and transmission fields) to which I believe they could be applied.

I am a doctoral student (nearing completion) in materials engineering at the University of Michigan. My work is on ceramic-to-metal adhesion and is strongly involved with thin film processes (especially RF Sputtering). I would like to do research on crystal and epitaxial film growth and this is why I find your research to develop oriented and packed pyramidal crystals so interesting.

I did a literature search and did not able to find anything authored by you on this topic. I would be very grateful if you could send me references or any papers on this work (especially on how the antennae work).

Thank you.

Sincerely,

Warren C. Wagner

Warren C. Wagner
1685 Broadway #101
Ann Arbor, MI 48105

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37922

July 20, 1987

Erich Farber
Solar Energy and Energy Conversion Lab
MEB 338
University of Florida
Gainsville, Fla. 32611

REF: AMI-RDN-7025

Dear Mr. Farber:

I spoke with you on the telephone on 7/20/87 concerning the article in "Advanced Materials and Processes" on your very interesting solar energy conversion system.

American Matrix has a unique technology for growing single crystal particles of various materials. Please review the company brochure and call me if we have mutual interests.

Sincerely,

Dick Nixdorf
Vice-President of Research
and Development

RDN/lsw

Enclosure

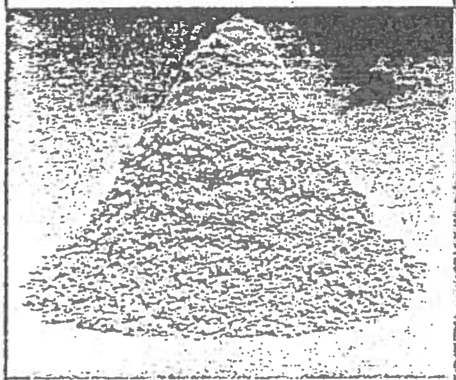
HIGH PURITY CERAMIC POWDERS

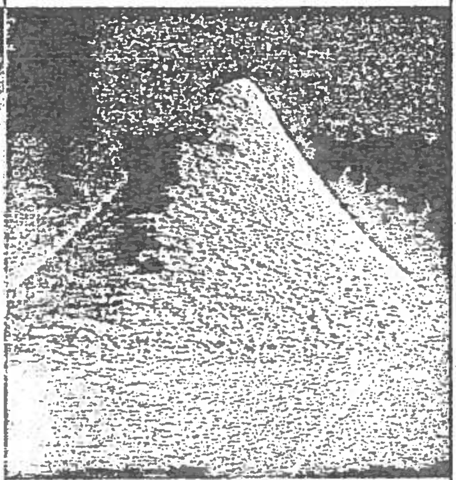
Boron Carbide

- Boron Content to 79%
- Particle Size from 3 Micron Mean
- Highly Sinterable

Zirconium Diboride

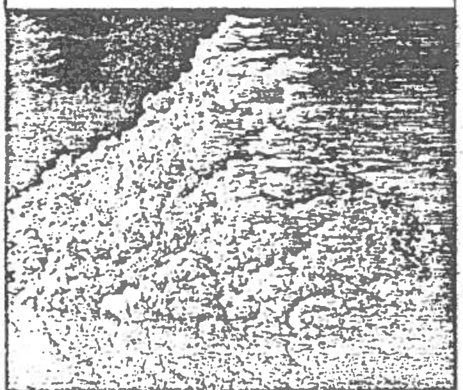
- 99.5% Chemical Purity
- Ceramic with Electrical and Thermal Conductivity of a Metal





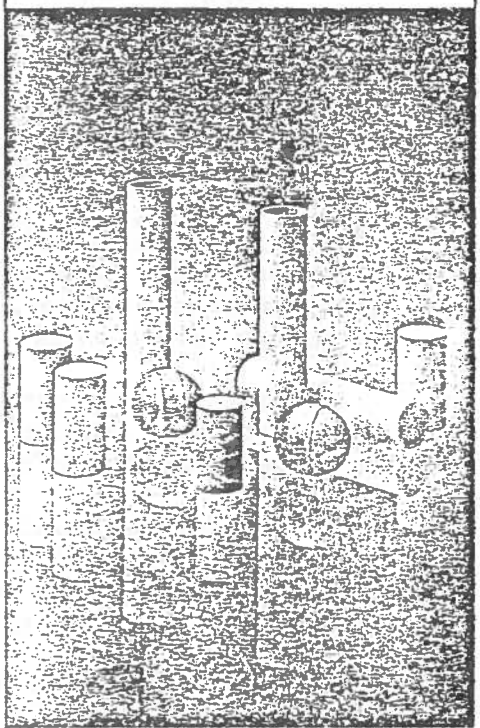
Silicon Carbide

- Alpha or Beta Phase
- Purity Availability to 99.9%
- Particle Size from 3 Micron Mean
- Excellent Sintering Characteristics



NUCLEAR CERAMICS

- American Matrix's engineering team has supplied the nuclear industry with ceramic control materials for over 15 years.



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July 20, 1987

Professor Erich Farber
University of Florida
College of Engineering
Department of Metallurgical and Materials Engineering
Gainesville, FL 32601

Dear Professor Farber:

I read the article in the July 87 issue of Advanced Materials Processes concerning your research on antennae for converting light waves to electrical energy. It was very interesting. I have to admit, I don't know how it works.

Using silicon carbide in the sand paper forms as an antennae and your problem of random orientation of the silicon carbide crystals raised a question in my mind. Could a recrystallized silicon carbide body work?

We regularly manufacture silicon carbide elements. The process is a sintering of grains of green silicon carbide. The bonding occurs by growing a lattice structure between larger silicon carbide grains. The final element is 99% pure silicon carbide.

The elements when heated are excellent emitters of infrared energy (.9), therefore should be good susceptors of energy.

Our most common shapes would be rods or cylinders. We can make plates and probably can make cones and pyramids.

If you have any interest in this material, please let me know the size and shape and I will send you samples.

Sincerely,

J.R. Davis

J.R. Davis,
President

JRD:kao

Inventors Claim Tiny Antennae Can Solve The Energy Problem

"The entire electricity supply for the United States can be generated from an area 150 miles by 150 miles using my patented inventions," claims Dr. Alvin Marks, chief scientist for Phototherm Inc. of Amherst, New Hampshire. The inventions, known as lepcon and lumeloid, convert sunlight to electric power at between 70 and 80 percent efficiency, says Marks. But some industry executives aren't sure if the technology is all that it is said to be.

BY EDWARD OVERELL

Both technologies work in a similar way, although the lepcon panels are made of long lasting metal-on-glass, and lumeloid is a short-lived type of plastic film. Both materials have tiny built-in antennas and diodes that convert sunlight into electrical energy. The lepcon panels are made by using a submicron electron beam writer to lay down the features on the metal. Marks says the manufacturing equipment needed for the metal lepcon panels would cost between $10 and $30 million. "If we had the money today it would take us about 18 months to get into production," he added.

The efficiency of photovoltaic cells depends on how the sunlight is processed by the cell, says Marks, who says his system is "easy to understand if you think of an indoor TV set antenna....If the signal from the TV station hits the antenna at the proper angle, you get a clear signal. If you turn the antenna to another position the signal gets much worse." Phototherm's technology, he adds, "works just like the TV signal hitting the antenna at the most efficient angle. In both designs, the sunlight gets to the collectors more efficiently than conventional photovoltaic cells."

Marks says his lepcon glass panels will be most economic for large-scale solar electric power farms. Laboratory experiments indicate 400 watts of electric power can be produced with one square meter of lepcon panel. Marks reasons that a 150-mile square of panels placed in the Southwest will produce 23 million megawatts of electricity per day—enough to meet the entire U.S. demand. Marks says the cost of production will be only one cent per kilowatt hour. For nighttime use, Marks told *New Technology Week*, "electric energy storage technologies are known and are being developed to serve this requirement."

The technology is not without its skeptics, however. "It's a nice concept, but it needs what I would describe as post-year-2000 technology," says Edgar Demeo program manager of advanced power systems at the Electric Power Research Institute. "There are very substantial practical problems because the dimensions of the antenna element would have to be very small, a small fraction of a micron," explains Demeo. The peak efficiency of an antenna is a single wavelength, but to receive solar energy efficiently the antenna has to be able to receive a wide range of wavelengths. "My sense is the [lumeloid and lepcon] concept would require what radio people call a broad band antenna," Demeo says, adding, "the price you pay for that is a reduction in efficiency."

"I haven't seen any evidence whatsoever of their research results," says Paul Maycock, president of PV Energy Systems, and one-time head of the Department of Energy's photovoltaic program. "They continue to impress people with their headlines, but I want to see some data."

But wouldn't it be in Phototherm's best interest to keep the specifics of the technology proprietary? "You keep things proprietary when you don't have anything," Maycock comments. "If they had a working model at 70 percent efficiencies, and were getting 70 watts

(Continued on page 5)

Sematech Quickly Setting Up Shop

Two electronics industry giants—IBM and AT&T—are transferring some of their most advanced memory products to Sematech to be used as manufacturing demonstration vehicles (MDV), which will hopefully move U.S. semiconductor manufacturing technology back into a world leadership position.

"Sematech's product is manufacturing knowledge," said Charles Sporck, board chairman of Sematech and chief executive officer of National Semiconductor Corporation. "We have selected two MDVs to facilitate the fast start-up of a flexible manufacturing capability that can meet the industry's needs for a wide variety of product families." With the products provided by IBM and AT&T, Sematech will be able "to test a line and identify defects more quickly and easily than other circuits exhibiting variable interactions between circuit segments," says Sporck. "They allow us to improve the technology and drive it faster than we could with other more complex interactive circuits...and we can measure progress into Phase II of our plans—targeted at 0.5 micron geometries."

IBM and AT&T hope that by giving their most advanced technology to Sematech, they will quickly gain from the research results that will be available to them as members of the consortium. "Sematech will be a rich source of ideas for IBM," said Jack Kuehler, executive vice president of IBM.

IBM contributed a four-megabit dynamic random access memory (DRAM) device plus all the manufacturing and engineering support necessary for efficient technology transfer. The device is about 1/2-inch by 1/4-inch and has a data access time of 65 nanoseconds. It is built using a modular process architecture which allows for the construction of static random access memory (SRAM) devices or logic chips, with only minor changes to the process sequence.

AT&T transferred a 64-kilobit SRAM device to the consortium. It is of the "six-transistor cell" type utilizing 0.7 micron geometries and is built with a type of process technology designed for making circuits such as logic chips and microprocessors. This type of chip has been used as a "yield driver" for AT&T's most advanced semiconductor manufacturing lines.

Sematech's goal is to demonstrate a flexible manufacturing capability that meets the low, medium or high volume needs of modern semiconductor factories.

Japanese Offer Olive Branch, Advice To U.S. Semiconductor Industry

The trade sanctions imposed on the Japanese electronics industry by the U.S. government should be lifted as soon as possible, says the Japanese semiconductor industry. In a report aimed to counter criticism that Japan has too big a share of its domestic electronics market, the Electronic Industries Association of Japan [EIAJ] offers an olive branch to the U.S. semiconductor industry, as well as some constructive criticism.

In the olive branch category, EIAJ says that it would like the cooperation of the U.S. in compiling a worldwide semiconductor demand and supply forecast. The Japanese also call on the U.S. to come to a better understanding of Japanese trade practices and customs. The report denies that Japan had promised U.S. semiconductor suppliers 20 percent of Japan's semiconductor market by 1991.

While Japanese producers control 90 percent of the domestic market, the Japanese complain that low-quality semiconductors hurt U.S. sales there, according to EIAJ. However, most of the major electronics manufacturers have programs aimed at increasing foreign semiconductor imports. The Japanese semiconductor market is "completely open and competitive" for high quality products, says EIAJ.

"Most of this is old hat," counters Jean Locke, director of communications at the (U.S.) Semiconductor Industry Association. "At every meeting attended by the Semiconductor Industry Association with the Japanese, the 20 percent market share [of the Japanese semiconductor market by 1991] was understood by both sides as an objective," Locke says. "The quality of U.S.-made products is not a problem now."

Locke says that the Japanese "only open their markets when sanctions are imposed." For instance, the market share of U.S.-made semiconductors did increase after the U.S. imposed sanctions, Locke explained. The sanctions were originally imposed after Japan failed to open up its market as specified in the United States/Japan semiconductor agreement signed in September 1986. "We have no problem in working with the Japanese to learn more about each other's markets," says Locke. "We will also cooperate with the Japanese in studying worldwide trade in semiconductors."

Still, exports of U.S. semiconductor products to Japan are not increasing at a rate "anywhere near what would be needed to reach the 20 percent market share." says Locke. "We are not on track to reach that figure."

U.S. semiconductor sales to Japan increased in the latter part of 1987, but have leveled out during the last two months, says SIA. Meanwhile, sales of all foreign-made semiconductors in Japan increased 27 percent to $115 million between June and August 1987, says the EIAJ report.

"SIA," says Locke, "has calculated that U.S. manufacturers have already lost $165 million in sales that would have been made if we were making real progress to reach the 20 percent figure by 1991. If we don't reach the 20 percent figure, U.S. exporters will lose between $5 and $6 billion in sales between now and 1991."

All major Japanese electronics manufacturers are actively trying to buy more foreign-made components, according to the report. Sony Corporation now purchases components from 55 foreign companies compared to buying from only 45 Japanese companies.

But some Japanese manufacturers interviewed about their efforts to purchase U.S. made semiconductors reported a lackadaisical attitude on the part of American suppliers. Fujitsu Corporation, Japan's largest computer vendor, complained about the lack of Japanese language manuals and quality evaluation data from foreign suppliers, the report says.

Another major Japanese appliance manufacturer, Sanyo Corporation, ordered 59,000 16-bit microprocessors from a U.S. company, but had to change to a Japanese supplier at the last minute when the U.S. vendor could not meet the promised deadline, according to the report. In another incident, Sanyo quality control engineers found corrosion on the chips when they were considering

(Continued on page 13)

Tiny Solar Antennae...

(Continued from page 3)

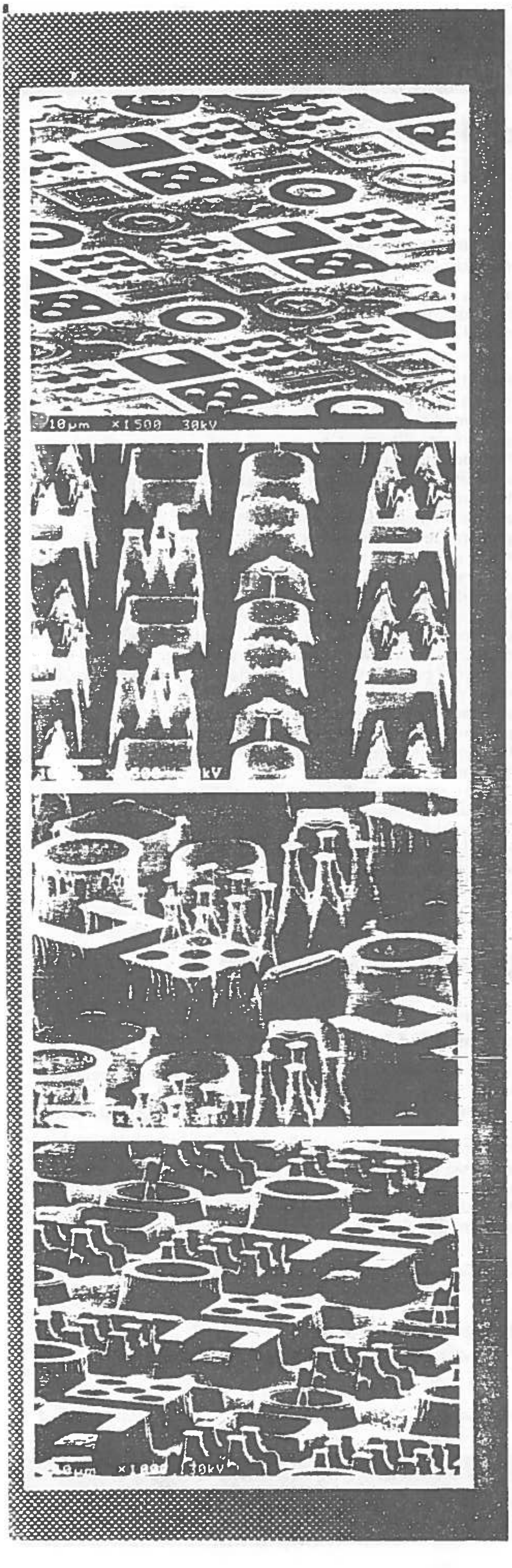
per square foot, the world would beat their door down."

In developing the lumeloid technology, Marks borrowed the concepts surrounding green plant photosynthesis. Marks says he uses synthetic chemicals to mimic the photosynthesis process. Lumeloid, the plastic version of the technology, is designed to generate electricity for individual households.' It is designed to be very inexpensive.

Lumeloid is made from an organic polymer film and will be manufactured eight micrometers thick. To get lumeloid film to work well, it is important to have the tiny antennas and diodes embedded in the polymer film and lined up in a parallel position, he said. "I've had a lot of experience with polarized film and I know about photosynthesis in plant life so I put the two together to produce lumeloid."

Manufacturing the lumeloid will be cheap, says Marks. He plans on using a similar method and equipment as that which is used in making polarized film. He estimates it will cost $5 per square meter to produce the lumeloid, which is made up of a support sheet, an eight micrometer thick continuously cast polymer film, the electrodes and lamination. He expects that it will sell for $15 per square meter. But with a lifespan of 6 to 12 months, the lumeloid is a throw away product. In terms of consumption, Marks likens the lumeloid to razor blades. "The investment cost will be one cent per watt spread over an expected life of 6-12 months in strong sunlight."

Marks estimates that one square meter of lepcon glass panel can be manufactured for $250, and should sell for $500. "One panel will produce 400 watts of electric power in bright sunlight,' Marks calculates, adding, "the cost of the lepcon works out to 50 cents per watt if spread over an expected life of over 25 years." Lepcon panels he predicts will be a perfect power source for outer space.



Announcement and Call for Papers

SPIE's 1988
Santa Clara Symposium on
MICROLITHOGRAPHY

Electron-Beam, X-Ray, & Ion-Beam Technology: Submicrometer Lithographies VII

Advances in Resist Technology & Processing V

Integrated Circuit Metrology, Inspection, & Process Control II

Optical/Laser Microlithography

Tutorial Educational Program
Instrument Exhibit

28 February - 4 March 1988
Santa Clara Marriott Hotel
Santa Clara, California USA

Sponsored by:

SPIE—The International Society for Optical Engineering

Electron-Beam, X-Ray, and Ion-Beam Technology: Submicrometer Lithographies VII

Conference Chair: **Arnold W. Yanof,** AT&T Bell Laboratories
Cochairs: **Daryl Ann Doane,** DAD Technologies, Inc.; **Nick P. Economou,** Micrion Corporation; **Katsumi Suzuki,** NEC Corporation (Japan); **John C. Wiesner,** Perkin-Elmer Corporation

The advent of excimer laser deep UV printing guarantees that the manufacture of optical steppers at 0.5 micron and below will be possible. But shallow depth of focus threatens to limit process latitude and complex resist systems threaten to increase process complexity and cost.

X-ray lithography using high brightness sources promises impressive advantages in the manufacture of semiconductor devices: high throughput, conventional single-level resist, large field size, wide process latitude, etc. The outstanding problem is the x-ray mask. In many locations around the world, there is now fierce competition between optical and x-ray lithographies to gain supremacy in future high volume manufacturing technology.

Electron-beam technology is unsurpassed for resolution, overlay capability, and circuit design turn-around time. Furthermore, the total cost for electron-beam lithography is falling as multilayer resist techniques allow the use of more sensitive resists with marginal plasma resistance. Further evolution in machine design promises increasingly competitive electron-beam throughput.

Focused-ion-beam technology is being developed rapidly for a number of applications. Because of the relatively low current densities presently available, the greatest near-term impact will be in applications requiring small area coverage, such as the repair and editing of patterns on masks or wafers. With increases in current density and improvements in source technology for different ion species, focused-ion-beam systems could become important in other applications, including lithography and maskless implantation.

This conference will emphasize the development, application, and demonstration of x-ray, electron-beam, and ion-beam tools. Papers demonstrating the fabrication of integrated circuits are especially sought, as well as actual data which demonstrate machine and system performance. Novel approaches and new techniques that affect basic lithography issues will also be eagerly received.

Technical papers in the following categories are suggested:

X-Ray Lithography
- device fabrication by x-ray, radiation damage
- x-ray masks: all aspects
- synchrotron lithography
- high brightness compact sources
- x-ray lithography system considerations and beam-line technology
- alignment methods with overlay results
- practical limits on x-ray resolution
- x-ray resists
- direct x-ray assisted processing

Electron-Beam Lithography
- fabrication of integrated devices
- electron-beam damage to devices; substrate charging
- characterization of existing commercial tools
- measured pattern placement and field stitching accuracy, line edge roughness
- alignment techniques and overlay results
- proximity effects, choice of beam energy, multilevel resists
- high speed, low contamination wafer handling

Ion-Beam Technology
- circuit interconnect diagnosis and modification
- direct implantation/deposition/etching
- x-ray mask repair
- novel ion-beam processes for microelectronics
- ion-beam lithography
- improvements in optics and sources.

Advances in Resist Technology and Processing V

Conference Chair: **Scott A. MacDonald,** IBM/Almaden Research Center
Cochairs: **Daryl Ann Doane,** DAD Technologies, Inc.; **Elsa Reichmanis,** AT&T Bell Laboratories

This conference is a continuation of the highly successful series of conferences on resist technology and processing at the Santa Clara Symposium on Microlithography. As micron and submicron device lithography becomes a reality, numerous constraints will be placed on resist chemistry and processing technology. The purpose of this conference is to emphasize recent advances in the science and engineering of high performance resist materials and processing. It is intended that the conference stress new resist materials with emphasis on the chemistry of resist design and operation, advances in processing techniques and engineering (as it relates to materials), and process modeling.

Original papers are solicited on the following and related topics:
- chemistry and physics of resist processing
- new resist materials for photo, electron-beam, x-ray, and ion-beam lithography
- materials and processes for multilayer resist technology
- exposure and development modeling.

One-Page Technical Abstract Due Date: 24 August 1987
Camera-Ready Abstract Due Date: 4 January 1988 • Manuscript Due Date: 1 February 1988

Integrated Circuit Metrology, Inspection, and Process Control II

Conference Chair: **Kevin M. Monahan,** Philips Research Laboratories/Signetics Corporation
Cochairs: **Daryl Ann Doane,** DAD Technologies, Inc.; **Stephen J. Erasmus,** Hewlett-Packard Laboratories; **Talat Hasan,** Prometrix Corporation

During the next decade, microelectronic manufacturing technology is expected to have minimum design rules well below 2 μm. Many of the high density circuits will have design rules in the submicron range. If a 10 percent error budget is allowed on any given layer, it will be necessary to routinely measure dimensions and alignments to accuracies of a few hundredths of a micrometer. Furthermore, in some cases, it will be necessary to make these measurements repeatedly and automatically over whole wafers or whole cassettes of wafers and to reference them to an appropriate standard. Concomitant with making critical dimension measurements is the requirement for detection of deviations from an ideal pattern. Inspection, locations, and classification of defects are rapidly becoming equally critical technologies for process control.

Recently, some exciting new technologies and some refinements of older technologies have been developed to cope with these problems. In optical metrology, we expect to see much greater use of automation, pattern recognition, deconvolution, induced fluorescence, induced current, and confocal laser techniques. As critical dimensions drop below 1 μm, the large depth of focus, small sample width, and inherently high resolution of scanning electron beams will be increasingly exploited. Electrical metrology, which lends itself naturally to automation and whole-wafer mapping, will be used to characterize the performance of lithographic and etch-patterning systems. Alignment metrology, currently the limiting technology for lithography, will become much more sophisticated as better alignment marks are devised and sensitive pattern recognition algorithms are implemented. Defect inspection will progress along a broad front by tailoring optical, electron-beam, and electrical techniques for specific purposes. Finally, powerful mathematical tools such as statistical experimental design and response surface methodology will be applied to minimize the cost of experimentation and gain control over the enormous amounts of process data.

Original papers are solicited on advances in the state of the art in integrated circuit metrology, inspection, and process control. The following and related topics will be considered:

- optical metrology
- scanning electron-beam metrology
- electrical pattern metrology
- alignment metrology and registration
- new measurement standards
- statistical design and modeling
- pattern recognition and image enhancement
- automated inspection and defect detection
- emerging technologies in microscopy.

Optical/Laser Microlithography

Conference Chair: **Burn J. Lin,** IBM General Technology Division
Cochairs: **John H. Bruning,** GCA Tropel, Inc.; **Mung S. Chen,** Intel Corporation; **Daryl Ann Doane,** DAD Technologies, Inc.; **Kanti Jain,** IBM Corporate Headquarters; **Victor Pol,** AT&T Bell Laboratories; **Akiyoshi Suzuki,** Canon Inc. (Japan); **Steve Wittekoek,** ASM Lithography (Netherlands); **Frederick Y. Wu,** Perkin-Elmer Corporation
Honorary Past Chair: **Harry L. Stover,** ASET

The true test for a lithographic technology lies in its usefulness in manufacturing. This includes producing the critical dimensions and critical overlay with high yield and low cost, easiness to practice, and timeliness to implement. Based on this, optical lithography undoubtedly still sets the pace as a manufacturing technology for generations of products to come. In the previous years, this symposium has provided a forum for refining existing techniques as well as introducing innovations to address manufacturing needs. As high technology accelerates, more papers whose coverage ranges from the necessary scientific understandings and innovative conceptions to device fabrication and product manufacturing are anticipated. Excimer laser lithography, which attracted many participants in 1987, is expected to blossom into higher sophistication toward device fabrication. The main stream optical lithographic concerns consisting of aligners and applications, pattern transfer, and masks are expected to hold their places as important topics to cover.

Papers on innovative and useful advances in the following and related topics are solicited:

Excimer Laser Lithography
- aligners, sources, condensers, lenses
- optical materials, material damage, speckles, vibration, contamination
- resolution, depth of focus, linewidth control
- device fabrication, manufacturing concerns

Optical Lithography: Aligners and Applications
- step-and-repeat, scan-and-repeat, and full-wafer projection aligners; proximity aligners; deep-uv, mid-uv, and near-uv systems
- lenses, condensers, alignment systems, wafer stages, focusing
- resolution/overlay improvements, depth of focus, proximity effects, in situ characterization
- lithography-related device performance and yield, process monitoring, contaminations
- throughput improvement, operational methodology, automation, equipment coupling

Optical Lithography: Pattern Transfer
- dry-etching, wet-etching, lift off, plating, stripping, cleaning
- systems, processes, monitoring, characterization
- selectivity, uniformity, rate, linewidth control
- contamination, defects, damages

Optical Lithography: Masks
- optical mask making, CD control/placement, inspection
- defects, repair, protection, contaminations
- special mask patterns for resolution/overlay/defect monitoring
- new mask technology.

Author Application

(This form may be photocopied)

SPIE's 1988 Santa Clara Symposium on Microlithography
28 February-4 March 1988 • Santa Clara Marriott Hotel • Santa Clara, California USA

One-Page Technical Abstract Due Date: 24 August 1987
Camera-Ready Abstract Due Date: 4 January 1988* • Manuscript Due Date: 1 February 1988
Note: Late submissions may be considered, subject to program time availability and chair's approval.

One-Page Technical Abstract, Application, Biography:
By 24 August 1987, SPIE must receive:
- 4 copies of the author application
- 4 copies of a brief professional biography
- 4 copies of a 400-600 word abstract, typed double-spaced on

8 x 11 white paper. Selection of papers will be based on the technical, novel, and informational quality of the work as described in the abstract. Authors are encouraged to include graphs or data in their abstracts where possible. Commercial papers, descriptions of products with no research content, and papers where supporting data or a technical description cannot be given for proprietary reasons will not be accepted for presentation in this symposium.

Please list on your abstract and on the form below the exact order of authors, with the principal author first, followed by co-authors. Give complete affiliation, complete mailing address (including mailstop, department, box no., etc.), and phone number for each author and co-author.

Mail to: SPIE Technical Program Committee/Micro '88
P.O. Box 10, Bellingham, WA 98227-0010 USA
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Telephone: 206/676-3290 (Pacific Time); Telex 46-7053

Notification of Acceptance: If your paper's abstract is accepted for presentation at the conference and inclusion in the Proceedings, you will receive a manuscript kit by 19 November 1987, which will include complete instructions for the preparation of your manuscript.

*Upon acceptance in the symposium program, principal authors will be sent instructions for preparation of a camera-ready abstract. All presentations made at Micro '88 will be represented in a book of abstracts to be distributed at the symposium. **Authors will be required** to submit this additional 500-word camera-ready abstract to SPIE **no later than 4 January 1988.** Authors are required to submit a draft manuscript to the Micro '88 Technical Committee for review prior to presentation at the meeting. Papers that the Technical Program Committee feels are purely marketing presentations will not be accepted for presentation.

Manuscript: After acceptance, a complete manuscript on SPIE-furnished manuscript paper must be submitted by 1 February 1988. Company and/or government security clearance to present and publish should be final at that time. All papers accepted will be considered released for copyrighted publication in the Proceedings.

Oral Presentation: Each presenter is generally allowed 15 to 20 minutes for presentation, plus a brief discussion period (about five minutes). SPIE will provide the following media equipment free of charge: 35mm Carousel slide projectors, overhead projectors, and electric pointers. Additional equipment may be arranged by SPIE at the speaker's expense.

Reduced Registration Fee: Authors and co-authors who attend the conference will be accorded a reduced-rate registration fee (which includes other special benefits).

Cancellation Policy: Because arbitrary cancellation is detrimental to the presenter's reputation and that of the Society, as well as causing losses of time, travel, and money to attendees, SPIE considers unprofessional the withdrawal or cancellation of a paper after it has been accepted and widely advertised to the technical community. Please secure sufficient funding and approval to insure your presence and participation in the conference.

To assist in the placement of your paper in the conference, please provide the following information by checking the appropriate box. Do you consider your paper to be *primarily*

- ☐ a technical description of a new product or system not previously published
- ☐ a technical description of the application of a system or comparison of systems used for the solution of a problem of general interest to the IC community
- ☐ a description of a new technical approach to solution of a problem in IC fabrication
- ☐ a description of new technology with application to IC manufacture
- ☐ other ______

☐ **I wish to submit** a paper in English for presentation at the conference checked below, and for publication in the proceedings of hat conference. Attached are four copies each of this author application, of my abstract, and of my professional biography. If my paper is accepted for presentation and publication, I agree. (1) to initiate at once any necessary company and/or government clearance procedures†; (2) ***to submit my camera-ready abstract to SPIE by the due date; (3) to submit my complete manuscript on SPIE manuscript paper by the manuscript due date*** (4) to release my paper for copyrighted publication in the Proceedings; and (5) to secure sufficient funding and approvals to insure my presence and my participation in the conference.

Principal Author's Signature: ______ **Date:** ______

- ☐ **Electron-Beam, X-Ray, and Ion-Beam Technology: Submicrometer Lithographies VII**
- ☐ **Advances in Resist Technology and Processing V**
- ☐ **Integrated Circuit Metrology, Inspection, and Process Control II**
- ☐ **Optical/Laser Microlithography**

Paper Title ______
If an acronym is used, please spell out its meaning, then enclose the acronym in parentheses.

	Principal Author	Co-Author (if none, write "none")
Name & Title		
Company or Affiliation (as it should appear in the program) ...		
Complete mailing address		
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Telex No.		

†Important note: It is essential that U.S. authors, subject to U.S. Government clearance, initiate all necessary clearance procedures at least 60 days prior to presentation.

For each additional co-author, attach the required information to this application.

REQUESTS FOR INFORMATION: Please send ☐ complete program when available; ☐ SPIE membership application.

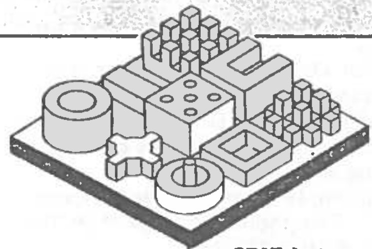
Invitation

WE INVITE YOU TO PARTICIPATE in SPIE's 1988 Santa Clara Symposium on Microlithography. The 1988 symposium will continue the expanded conference program presented in 1987, with the second annual conference on integrated circuit metrology, inspection, and process control. The annual conference on optical microlithography has been expanded to present important sessions on lasers in microlithography, and the advances in resist technology and processing conference will emphasize techniques for submicron dimensions. The seventh annual conference on electron-beam, x-ray, and ion-beam lithographies will complete the program. The familiar and successful poster sessions, presenting topical papers in relation to each conference, will continue to be an exciting attraction, serving the dual purposes of technology transfer and social interaction. A full tutorial program addressing all topics covered in the conferences also will be presented.

We welcome your participation in this symposium and encourage you and your colleagues to submit papers on your work related to the conferences described in this Call for Papers.

Diana Nyyssonen,
CD Metrology, Inc., *Microlithography 1988 Symposium Chair*

William L. Wolfe,
Optical Sciences Center/University of Arizona, *1987 Symposia Planning Committee Chair*



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or Information about Exhibiting in Santa Clara

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Meetings of related interest

One conference at SPIE's 31st
Annual International Technical Symposium on
Optical and Optoelectronic Applied Science and Engineering

16–21 August 1987
Town & Country Hotel • San Diego, California USA

X RAYS FROM LASER PLASMAS
Chair: **Martin C. Richardson,** University of Rochester

Two conferences at SPIE's International
Symposium on the Technologies for Optoelectronics

16–20 November 1987
Palais des Festivals et des Congrès • Cannes, France

QUANTUM WELLS AND SUPERLATTICES IN OPTOELECTRONIC DEVICES AND INTEGRATED OPTICS
Chair: **Alfred R. Adams,** University of Surrey (UK)

ADVANCED OPTOELECTRONIC TECHNOLOGY
Chairs: **D. B. Ostrowsky,** Université de Nice (France);
Claude Puech, Thomson-CSF/LCR (France)

SPIE's Symposium on
ADVANCES IN SEMICONDUCTORS AND SEMICONDUCTOR STRUCTURES
13–18 March 1988
Newport Beach Marriott Hotel • Newport Beach, California USA
Symposium Chair: **Fred H. Pollak,** Brooklyn College/CUNY

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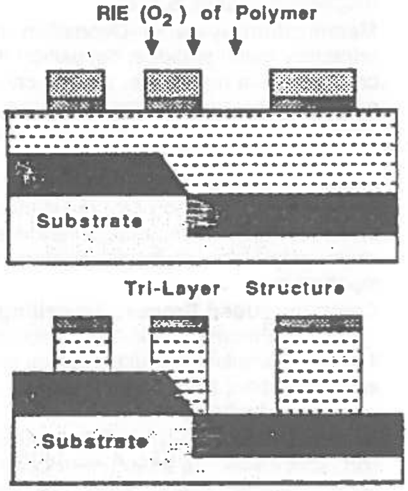
University of California, Irvine
Department of Electrical Engineering
University Extension

Two
Intensive
Seminars

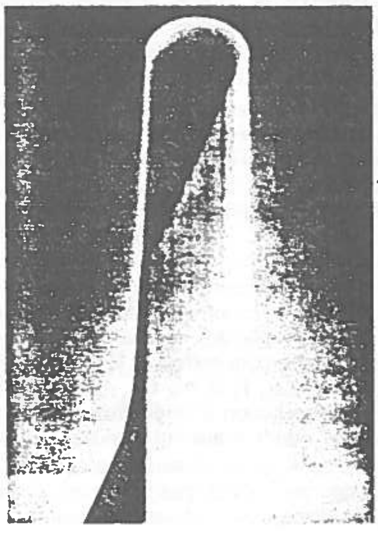
SILICON PROCESSING FOR THE VLSI ERA



A comprehensive five-day overview of current processing techniques utilized to fabricate VLSI circuits.

June 20-24, 1988
in Costa Mesa, California

PLASMA PROCESSING AND SPUTTERING TECHNOLOGIES IN MICROELECTRONICS



A NEW course reviewing state-of-the-art and exploring applications of sputtering, deposition and etching technologies for manufacturing of microelectronic components.

June 27 - July 1, 1988
in Costa Mesa, California

SILICON PROCESSING FOR THE VLSI ERA

JUNE 20-24, 1988

Introduction

As the feature sizes on integrated circuits shrink to less than 1 micron and chip sizes increase beyond I cm2, the fabrication processes required to successfully manufacture such complex circuits are undergoing revolutionary as well as evolutionary changes. The purpose of this course is to provide a detailed introduction to state-of-the-art process techniques used in fabricating silicon integrated circuits.

Professionals often enter the semiconductor industry without complete knowledge of the processing technologies with which they will be working. Even experienced engineers may find little time to keep abreast of the latest technologies except in areas of their immediate need for information. This course is designed to give such individuals a comprehensive overview of the current processing techniques that are utilized to fabricate VLSI circuits.

Who Should Attend

Engineers involved in integrated circuit device design, process development, manufacturing, equipment design, sustaining, test, applications and marketing. Managers of integrated circuit fabrication facilities. For those who have recently entered the industry, the course provides a rapid in-depth exposure to the entire semiconductor fabrication cycle, while more experienced engineers will benefit from a thorough and timely update on the technical trends emerging in each area of the manufacturing process.

Familiarity with current fabrication technology is also of critical importance to today's VLSI designers. Not only are design decisions and trade-offs influenced by processing advances and limitations, but effective interfacing with IC fabrication facilities/ foundries is enhanced when the designer understands the nuances of "wafer fab."

Topical Outline of the Course

Introduction--Silicon processing state-of-the-art today; device scaling and its implications to silicon processing; where will silicon processing be in five years?

VLSI Fabrication Facilities--Contamination control-cleanliness standards and clean rooms, DI plant; equipment requirements, including environmental and safety considerations; managing a fabrication line; factors impacting manufacturing yield.

Silicon Materials--Polycrystaline preparation: single-crystal growth, including Czochralski and float zone purification techniques; influence of incorporated carbon and oxygen; wafer preparation; silicon defects including process-induced defects; gettering; annealing damaged and amorphous layers (heat, laser, etc.).

Epitaxial Deposition--Theory of growth; reactions and kinetics; growth of epi layer--a process sequence; evaluation of epi layers, including sheet resistance, thickness, spreading resistance, defect densities, modern epi reactors: molecular-beam epitaxy.

Oxidation--Wafer cleaning (manual, auto), the oxidation process (wet, dry, and high-pressure); the oxidation apparatus--furnaces (DDC), boats, sources of oxidants; the oxide--thickness (including evaluation of), dielectric strength, capacitance, etch rates, index of refraction, oxide charge, annealing; selective oxidation--Si3N4 oxidation, "birds beak," encroachment; gate oxide growth--very thin oxides (70-150 Ao), cleanliness, stability.

Diffusion--Predeposition-equations, techniques; drive-in-equations, techniques; diffusion apparatus--furnaces, chemical sources (gas, solid, thin-film, liquid); evaluation of diffused layers--sheet resistance, surface concentration, junction depth; diffusion of various dopants (i.e., P, B, As, Ga, Al, Sb), anomalies, solid-solubilities; redistribution of impurities during epitaxy and oxidation; oxide and nitride masking; cumulative effect of heat cycles.

Ion Implantation--Advantages and problems; theory of ion implantation--collision processes, gas spectrum, range and straggle (including stopping power of various masks), channeling; residual damage and annealing; low, medium and high dose process characteristics; focused-ion-beams.

Lithography--Photoresists--negative, positive, coating, baking, surface preparation; pattern printing--uv, deep uv, x-ray, E-beam; aligning tools--contact, proximity, and projection aligners, direct-step-on-wafer aligners; aligning technology--manual, automatic, exposure, develop/rinse, inspection (strip rework); multi-level resist techniques for fine-geometry definition; linewidth control and measurement; mask making-optical and electron beam pattern generators.

Etching Technology--Wet (oxide, nitride, Si,Al, Pt, TiW, etc.); dry etching--physics and chemistry of plasma etching/ reactive ion etching (RIE)/ion milling/reactive ion beam etching (RIBE)/ magnetron ion etching (MIE); dry etching of oxides, nitrides, Al alloys, silicides,and PR stripping; issues of etching--isotropic and anisotropic etching, selectivity, end-point detection, mask erosion and adhesion to substrate materials, dry-etch difficulties and advantages; dry-etch equipment--barrel, planar, hex, and single-wafer configurations.

Chemical Vapor Deposition--Equipment (hot wall, cold wall, low pressure, plasma-enhanced); equations of CVD (introduction) and important reactions (SiO2, Si3N4,, polysilicon, and refractory metal silicides); passivation films and interlevel dielectrics, such as PSG, BPSG, ASG, PGSG, and spin on glasses.

Physical Vapor Deposition--Introduction to VLSI vacuum technology (mechanical, cryo, diffusion, turbo pumps); pressure measurement (TC, ionization gauges); evaporation techniques; sputtering--basic theory and equipment, diode (DC/RF), magnetron (planar, S-gun).

Metallization Systems--Deposition of platinum, Al, Al alloys, refractory metal silicides; deposition monitoring; metallization concerns--film resistance, current carrying capability (electromigration), contact resistance, step coverage, corrosion, ohmic contacts, barrier metals to prevent aluminum-silicon interdiffusion; multi-level metal schemes and problems--step coverage over underlying polysilicon and metal steps, hillocks and pinholes, step coverage into VIAs, contact resistance between M1 and M2 layers, test structures, multi-level dielectrics (CVD oxide, PECVD oxide, polyimides, etch-back techniques to produce planarized topography).

Computer-Aided Process Modelling and Simulation--Stanford University Process Engineering Models Program (SUPREM), what it does. examples; two-dimensional process simulation programs--an introduction; sub-micron transistor device characteristics and processing techniques.

Assembly, Packaging and Test--Assembly operation--probe/wafer sort, scribe/saw, die attach, wire bond, sealing; package types--plastic, ceramic, Cerdip, DIPs, chip carriers, and pin grid arrays; electrostatic protection; production test--parametric, functional, and burn-in testing; test equipment.

Process Integration--How the individual fabrication techniques discussed earlier in the course can be integrated to create complete VLSI manufacturing processes; example of state-of-the-art CMOS and bipolar process flow.

Manufacturability Issues for VLSI Fabrication Lines--Transferring and optimizing a process from R & D to the production line; maintaining the process in a production environment (role of process monitors and yield data as feedback to process-line engineers and managers); process-line personnel management, training and discipline; methodology for equipment selection; automation in VLSI fabrication facilities; the equipment sustaining effort; fabrication line/VLSI designer interface.

Analysis Techniques for Characterizing Semiconductor Processes--Scanning electron microscopy and microsectioning techniques; Transmission electron microscopy; Auger electron spectroscopy and scanning auger microscopy; X-ray photoelectron spectroscopy (ESCA); X-ray emission spectroscopy; Secondary ion mass spectroscopy; Rutherford back-scattering; Laser reflectance for stress measurement.

Updated and New Course Material for 1988

Rapid Thermal Annealing (RTA)--Application to VLSI, equipment configurations, implant activation in single and polycrystalline silicon, formation of Schottky barrier contacts, low resistivity interconnects (silicides) and ohmic contact metallization, reflow of interlevel dielectric glass and device applications.

Isolation Technologies--Isolation of MOS and bipolar devices; comparison of junction, LOCOS, SWAMI, and trench isolation techniques, silicon sapphire, silicon on insulator, and buried oxide technologies.

Multilevel Interconnect Technology--Planarization techniques (etch back, polyimides,"spacers", bias sputtered quartz, selective deposition for via refill), new metallization systems including blanket and selective tungsten deposition, aluminum-titanium alloys for electromigration and hillock suppression, etc.

Silicides--Why high conductivity interconnects, materials of interest (TiSi2, WSi2, TaSi2, MoSi2, and PtSi), effect of annealing, stoichiometry and preparation method on resistivity, oxidation of silicides, methods of formation (co-evaporation, co-sputtering, single target sputtering, chemical vapor deposition, and direct reaction), selective polycide and salicide processes.

Schedule

MONDAY-FRIDAY, JUNE 20-24, 1988

Registration: Monday, 8-8:30 am

Lectures: Monday through Thursday, 8 am-5 pm Friday, 8 am-1pm

Lunches: Monday through Thursday, noon-1:30 pm (there will be no lunch break on Friday)

Breaks: 10:15-10:30 am and 3:15-3:30 pm

Reception: Monday, 5-7 pm, complimentary wine and cheese

Workshop: Thursday, 5-7 pm

Moderated by the course instructors and lecturers, the workshop will allow attendees to discuss and pursue in further depth subjects of interest introduced in the lectures.

Location

The Red Lion Inn, 3050 Bristol Street, Costa Mesa, California, 92626-3098. Telephone (714) 540-7000 or 1-800-547-8010. You should make your own reservation by contacting the hotel directly. For details about your registration and the Red Lion Inn accommodations, please refer to the Plasma Processing and Sputtering Technologies section of this brochure under the heading LOCATION.

Fee

A fee of $1295 includes the textbook Silicon Processing for the VLSI Era, Vol. 1 by Stanley Wolf and Richard Tauber; and revised and updated course notes. Also included in the fee are daily lunches and complimentary refreshments at the reception.

Engineering 874

Faculty

Chuck DeHont, B.Ch.E., Director of die production at Sierra Semiconductor. He previously served as Plant Manager of Wafer Fab III. Intel Corp., Livermore, CA. Wafer Fab III is a fabrication facility for Intel's high-end microprocessors and also serves as a corporate new technology development site. Mr. DeHont will discuss manufacturability issues in VLSI fabrication lines.

Simmon A. Prussin, Ph.D., is a Consulting Engineer working in semiconductor materials, silicon crystals, defects, ion implanting, annealing, and gettering. In 1960 Dr. Prussin founded Monosilicon, Inc., the first silicon producer to offer dislocation free silicon commercially. Active as a consultant since that time, Dr. Prussin has served TRW, JPL, Xerox Corporation and numerous other microelectronics companies. He is the author of numerous papers on semiconductor materials and processes, including Model for MOS Field-Time-Dependent Breakdown, which was awarded best paper of the 1978 International Reliability Physics Symposium.

Richard N. Tauber, Ph.D., Chief Scientist, Microelectronics, TRW, Inc. He previously served as manager of VLSI fabrication laboratory at TRW. Dr. Tauber's prior experience includes: head of IC Processing at Hughes Aircraft; IC Processing development for Xerox Microelectronics Center; member of technical staff, Bell Telephone Laboratories; and assistant professor of metallurgy and materials sciences at Lehigh University. Author of more than 25 technical papers on solid state materials and devices, he served as co-editor of the Proceedings of the Sixth International Conference on Chemical Vapor Deposition. His most recent accomplishment is the co-authorship of the text ***Silicon Processing for the VLSI Era, Volume I: Process Technology.***

Stanley Wolf, Ph.D., Associate Professor of electrical engineering, California State University, Long Beach. Dr. Wolf was employed by Hughes Aircraft Company, Microelectronics Research Center, prior to assuming his teaching position at CSULB in 1979. Currently a consultant on microelectronic device physics and fabrication processes at TRW, Inc., his specific interests include interconnect systems, dielectric materials as interlevel insulators, and materials characterization techniques for VLSI fabrication techniques. Author of ***Guide to Electronic Measurements and Laboratory Practice*** (2nd edition, 1983, Prentice-Hall), he most recently wrote "A Dry-Etch Process of Polyimides for VLSI Applications," which was presented at the Fall 1983 Electrochemical Society Conference. Professor Wolf is the co-author with Dr. Tauber of the text ***Silicon Processing for the VLSI Era Volume I; Process Technology.***

What Past Participants Have Said About the Course

In past years, this course and its faculty have received consistently excellent evaluations. The following quotes are representative of written comments by those who most recently attended the course:

"Very informative."

"Gave me a broad exposure to the subject."

"Text very fine and references very helpful."

"Brought my understanding up semiconductor manufacturing up to current levels."

"I understand better what kinds of problems my suppliers go through in introducing new processes or embracing old ones."

"Covered more depth than I expected."

Representative firms whose employees have been participants in the course:

Advanced Micro Devices
Allied Chemical
American Microsystems
Applied Materials
AT&T
Bipolar Integrated Technology
Branson/IPC
Cherry Semiconductor
Commodore Semiconductor Systems
Control Data
Delco Electronics
Eastman Kodak
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Sandia Laboratories
Shipley Co., Inc.
Signetics
Silicon Systems
Tektronix
Texas Instruments
TRW
U.S. Government (Dept. of Navy and FBI)
Unitrode
Western Digital
Western Electric
Xerox
Zilog
And many European firms

The courses described in this brochure are available for in-house instruction. For more information call the program director at UCI Extension. (714) 856-7978.

PLASMA PROCESSING AND SPUTTERING TECHNOLOGIES IN MICROELECTRONICS

JUNE 27-JULY 1, 1988

Course Overview

Plasma technology, or more appropriately glow-discharge technology, is utilized in a large number of process steps in VLSI fabrication. These steps include:

a) sputter deposition
b) dry etching; plasma, RIE, ion-milling
c) plasma-enhanced CVD: PECVD
d) gelectron-dash cyclotron resonance, etching, and deposition
e) reactive sputter deposition
f) plasma-enhanced oxidation and nitradation of silicon surfaces

Plasmas have been introduced into these processes for three reasons:

1) The plasma is basic to the process
2) The plasma enhances the process, or
3) The plasma allows the process to occur at a lower temperature than if no plasma is present.

The glow-discharge, however, is a complex state of matter, whose properties are dependent on a large number of inter-related parameters such as pressure, applied power, excitation frequency, pumping speed and gas species. In order to obtain optimal benefits from using the plasma, not only the role of each of these parameters must be well understood, but also the manner in which they interact in each application. The purpose of this course is to provide in-depth information on glow-discharge technology as utilized in various phases and steps of VLSI component fabrication.

Of the glow-discharge applications listed, this course will primarily emphasize sputter deposition for microelectronic applications. The basic science of sputter deposition, including dc diode, rf, and magnetron sputtering will first be covered. Then additional topics pertaining to sputtering will be explored, including: bias sputtering; sub-strate heating, planarized films by sputter deposition; the effect of contaminant gases on sputtered films; high-rate sputtering processes: control of stress and microstructure in sputtered films; sputtering equipment and sputtering targets; monitoring sputter processes: deposition of the following films-aluminum, aluminum alloys, refractory metals and their silicides, TI W, Pt, BSQ.

The lead lecturer and course organizer, Dr. Brian Chapman, has long been involved in applying glow-discharge technology to VLSI manufacture. His well-known book, ***Glow-Discharge Processes***, by John Wiley and Sons, 1980, was the first to be published on the subject. Currently Dr. B. Chapman is working on a revision of his highly acclaimed book, where latest advances in glow-discharge processing will be incorporated. Dr. Chapman will present the advanced, up-to-date information in this seminar.

Who Should Attend

This course is designed for engineers, scientists and technical supervisory personnel involved in development and fabrication of integrated circuits. Technologists involved in research, development and process engineering will expand their knowledge in state-of-the-art and future trends in plasma processing, glow discharge, sputtering, thin film deposition and etching technologies which are applied primarily to the fabrication of VLSI circuits with very high densities and submicron geometries.

In addition to the manufacturing of silicon-based circuits, plasma processing and sputtering technologies are finding increasing application in many other high-technology industrial applications, e.g., for thin film processing in magnetic and optical storage devices. Accordingly, this course should be of direct interest to a broader spectrum of technical and managerial personnel whose professional interests include design, manufacturing and quality control of thin film based microelectronic components, storage media and devices as well as development and maintenance of process equipment.

Topical Outline of the Course

I. GENERAL PRINCIPLES

Vacuum
- Behavior of low pressure gases
- Gas effects in plasma processing

Discharges
- The building blocks - ionization, dissociation and excitation
- Plasmas and glow discharges
- DC glow discharges
- AC discharges
- Magnetically confined discharges

Practical Matters
- Power supplies and matching networks
- Equipment considerations: process control and maintaining high yield
- Process development

II. SPUTTERING

Basic Principles
- Principles and implementation of sputtering
- Challenges in film deposition
- High rate sputtering
- Sputtering of insulators
- Reactive processes
- Bias sputtering
- Step coverage vs. bias
- Sputtering system configurations
- Modeling the deposition process
- Sputter etching
- Future of sputtering

High Rate Sputtering
- Principles of discharge confinement
- Sputtering with magnetron discharges
- Review of high rate sputtering cathode designs
- New applications for confined discharges

R.F. Sputtering
- How rf sputtering works
- Why 13.56 mhz?
- Self-bias

III. PLASMA CHEMICAL PROCESSES

Introduction
- Gas phase processes
- Sheath processes affecting ion bombardment
- Substrate processes controlling etching and deposition

Plasma Chemical Processes
- Glow discharge cleaning
- Plasma ashing and plasma stripping
- Plasma etching and RIE
- Etching system configurations
- Plasma deposition
- Microwave and other systems
- Other plasma-enhanced processes

IV. MATERIALS ISSUES

Thin Film Growth Kinetics & Structure

- Kinetic models of film growth
- Structure zones and dependence on adatom mobility
- Structure modification by ion bombardment
- Structural defects and solid state reactions

Materials & Processes for Sputtering

- Reasons for choosing aluminum
- Silicon diffusion and related issues
- Electromigration
- Hillock formation
- Step coverage vs. bias
- Refractories and other materials
- Other deposition techniques
- Future of sputtering

Materials & Processes for Plasma Chemical Processing

- Fundamental experiments in plasma etching
- Models for isotropic and anisotropic etching
- Multi-step processes
- Uniformity and selectivity
- Challenges in plasma chemical processing

V. ANALYTICAL TECHNIQUES

Plasma Diagnostics

- Optical emission spectroscopy
- Langmuir probes
- Laser induced fluorescence
- Microwave interferometry
- Mass spectroscopy

Surface Analysis Techniques

- Basics and comparisons of surface analytical techniques
- X-Ray Photoelectron Spectoscopy (XPS or ESCA)
- Auger Electron Spectroscopy (AES)
- Secondary Ion Mass Spectroscopy (SIMS)
- Rutherford Backscattering Spectroscopy (RBS)
- Ion Scattering Spectroscopy (ISS)
- Examples in plasma processing and other technologies
- Other analytical techniques

Future Trends

- Opportunities and technical challenges for future applications of plasma and sputtering technologies
- Discussions of major problem areas
- Limiting factors and directions for possible solutions

Schedule

MONDAY-FRIDAY, JUNE 27-JULY 1, 1988

Registration: Monday, 8-8:30 am

Lectures: Monday through Thursday, 8 am-5 pm Friday, 8 am-1 pm

Lunches: Monday through Thursday, noon-1:30 pm (there will be no lunch break on Friday)

Breaks: 10:15-10:30 am and 3:15-3:30 pm

Reception: Monday, 5-7 pm, complimentary wine and cheese

Workshop: Thursday, 5-7 pm

Moderated by the course instructors and lecturers, the workshop will allow attendees to discuss and pursue in further depth subjects of interest introduced in the lectures.

Location

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Engineering 874.4

Faculty

Christopher R. Brundle, Ph.D., has been with IBM Research for eleven years and is currently manager of Micro, Surface, and Analytical Science at the IBM Almaden Research Center. Prior to joining IBM, he taught in the Physical Chemistry Department of Bradford University, England. He is a Consultant Professor in the Chemical Engineering Department at Stanford University, and Editor of the Journal of Electron Spectroscopy. He is active in the American Vacuum Society as a regular Short Course Instructor and a past Chairman of the Surface Science Division.

Brian Chapman, Ph.D., is President of Lucas Laboratories, San Jose, California, specializing in contract research development and engineering for plasma applications. He received his M.A. in Physics from London College, University of Oxford, and his Ph.D. in Electrical Engineering from Imperial College, University of London, subsequently joining the faculty there. Two sabbaticals in the U.S. led Dr. Chapman to move from England, initially to join IBM Research. More recently he has shifted his focus from wafer fabrication to the research, development and engineering in plasma processes, process control and plasma systems. Dr. Chapman has published extensively, including "Glow Discharge Processes: Sputtering and Plasma Etching," John Wiley & Sons, New York, which is the text included with this course.

Walter Class, Ph.D., is the Director of Technology for the Thin Film Division of Eaton Corp. He has approximately twenty years of experience with sputtering processes and related plasma processes such as plasma etching. This experience encompasses sputter process development, magnetron sputter cathode development and characterization, as well as the application of magnetron discharges to related processes such as reactive ion etching, reactive sputtering and reactive bias sputtering. Dr. Class is a member of the American Vacuum Society and Electrochemical Society and holds a Ph.D. in Materials Science from Columbia University.

Kenneth R. Stalder, Ph.D., Physicist, SRI International. Dr. Stalder is a specialist in plasma diagnostics including techniques using Langmuir probes, microwave interferometry, and optical techniques. Prior to joining SRI International, Dr. Stalder was a Member of the Technical Staff at Applied Materials Inc., developing new plasma etching techniques. He was also a Research Specialist at UC Irvine, using lasers for non-invasive plasma diagnostics. He received his Ph.D. in Physics from UC Berkeley in 1982 and did research in atomic collision physics related to fusion plasmas at the Lawrence Berkeley Laboratory.

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1. A dielectric plate, possibly supported by other material is selected.

2. The dielectric layer is coated with a photo-sensitive conductive layer or a film of desired thickness (probably very thin).

3. The photo-sensitive film is exposed to a desired light pattern (photolithography).

4. After development there will remain areas of the insulating film while other areas will expose the conductive surface.

5. In this step the configuration of (4) is coated with a dielectric or electrically non-conducting film which is photo sensitive.

6. Exposing this last arrangement to the correct light pattern will produce the necessary chemical changes.

7. After developing the exposed new film, portions of the film will remain, forming the layered arrangement.

8. Next it is necessary to apply another photo-sensitive conductive coating.

9. Again exposing the sample to the correct light pattern the desired chemical changes are produced.

10. After development the layered arrangement or dot matrix shown in Figure 72 is obtained, giving the proper interconnection in the matrix.

11. The final step in manufacturing the ASETEC is to grow pyramids on each square of the dot matrix to give the required configuration with the correct interconnections for the conversion of solar energy to electricity.

Different connections of the individual units are possible and the formation of groups or blocks can be put in either series or parallel.

The different interconnecting layers may only be fractions of microns thick.

Manufacture of these configurations may not be perfect. Previous work demonstrated that perfect shapes are not needed for excellent performance and some of the surface conditions such as the waxed ones used in earlier work, did not seem to affect performance appreciably.

After the "Spot Matrix Arrays" described above or those of similar design are manufactured by the best methods and procedures still to be developed, although methods are available now to make them, they must be evaluated under laboratory lights and then with solar energy.

It is suggested that after the manufacturing techniques are developed and the resulting "Spot Matrix Arrays" evaluated, different materials be used such as SiC, other tetrahedral crystal configurations, also other products of fiber and whisker technologies (three-sided pyramids, three sided rods, such converging rods with a terminal sphere at the apex, etc.

Further optimization of the conversion performance such as parameter and effects should be investigated:

Direct and Diffuse Radiation (Combination)
Temperature Effects

Angle of Incident Radiation

Film Thickness

Exposure Time (short-term effects, long-term effects)

Grounding Configurations

Protective Coatings and Covers

Probe Size and Shape as Center of Crystallization

Different Probe and Transmission Line Materials (solids, liquids, etc.)

Combination of Different Size Elements

Efficient Rectification - if needed

Possible Combinations of Antennae and Rectification In One and the Same Array System.

More parameters could be cited but the most important are listed above and investigation priorities can be set at a later date. Some of these investigations can also be carried out at longer wavelengths, such as in the microwave range.

The results expected from this investigation and evaluation of the different "Spot Matrix Arrays" will include such things as:

1. Open Circuit Voltage
2. Short Circuit Current
3. Current versus Voltage Performance Curves
4. Maximum Power at Different Irradiation
5. Conversion Efficiencies.

This approach should lead to Solar Energy to Electricity Conversion devices which are more efficient than the Solid State devices available at the present time.

APPENDIX A

ASSORTED PAPERS, ARTICLES AND SEMINAR INFORMATION

Theoretical Method for Determining the Apparent Radiation Properties for Materials in Sinusoidal Configuration

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Mem. ASME

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This paper gives a theoretical method by which the apparent radiation properties, absorptance and transmittance, and reflectance can be determined knowing the respective flat material properties. This paper uses a similar approach but is mathematically different from a paper presented at the 1963 Solar Energy Symposium, where a rectangular configuration was the basis for analysis.

Introduction

This investigation was prompted, as the earlier paper, by our work with the University of Florida—ASHRAE Solar Calorimeter, and by the need for determining the solar heat gain, a quantity of importance in architectural design, and in the evaluation of heating and air-conditioning requirements. For this purpose it is necessary to know the physical properties of the various layers of fenestration.

This paper describes a method by which the apparent properties in sinusoidal configuration can be determined theoretically from the corresponding properties of the flat material, information usually available from the manufacturers.

Theoretically obtained values are, in many cases, considered better than the experimental results which vary somewhat depending upon the measuring method employed. Theoretically calculated values are close to the average of a great number of readings taken over a hanging drapery.

The following assumptions were made for the purpose of the theoretical analysis:

1 The sinusoidal configuration, as shown in Fig. 1, can be applied as a good approximation.
2 The physical radiation properties of the material are known.
3 The drapery materials are diffusely reflecting.
4 The folds are long compared with their width.

The sinusoidal configuration, assumption 1, was chosen since it is a good approximation, much better than the rectangular configuration of an earlier paper (which was chosen then since results in the literature could be used to reduce the tremendous amount of computer work).

Since radiation from the sun arrives at the drapery in part as direct and the rest as diffuse radiation, the analysis was divided into two parts:

(*a*) For diffusely incident radiation.
(*b*) For parallel ray incident radiation.

A. Diffusely Incident Radiation

With the diffuse solar radiation entering the fold of the drapery each point will give off energy both by fundamental radiation and by reflection of the incoming energy.

Referring to Fig. 1, the energy leaving point x_0, called radiosity $B(x_0)$, can be expressed by equation (1).

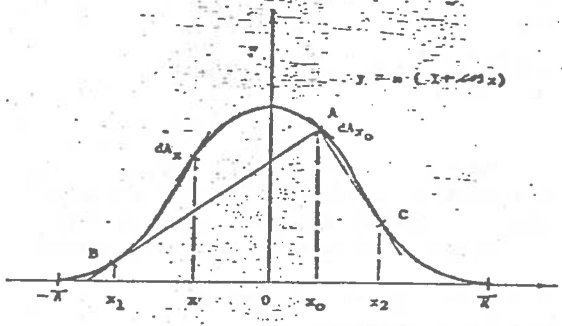

Fig. 1 Sinusoidal configuration

$$B(x_0) = (1-\rho)\sigma T^4 + \rho H(x_0)$$
$$= (1-\rho)\sigma T^4 + \rho \int_{x_1}^{x_2} B(x) dF_{x_0-x} \quad (1)$$

where ρ is the reflectivity of the flat material, σ the Stefan-Boltzman radiation constant, T the absolute temperature, $H(x_0)$ the incoming radiant energy, $B(x)$ the radiosity distribution in the fold, and dF_{x_0-x} the configuration factor between the unit area at x_0 and a strip of differential width at position x.

Dividing equation (1) by σT^4 the apparent reflectivity at point x_0 is found as shown in equation (2).

$$\rho a(x_0) = \rho - \rho \int_{x_1}^{x_2} [1 - \rho a(x)] dF_{x_0-x} \quad (2)$$

where $\rho a(x)$ is the reflectivity distribution in the fold.

Since the differential area at point x_0 can only exchange energy with the part of the fold which it can see, the end points x_1 and x_2 where the tangent lines from x_0 touch the fold must be found. This can be done by means of equations (3*a*) and (3*b*) requiring trial and error.

$$\sin x_1 = -\frac{\cos x_0 - \cos x_1}{x_0 - x_1} \quad (3a)$$

$$\sin x_2 = -\frac{\cos x_0 - \cos x_2}{x_0 - x_2} \quad (3b)$$

Utilizing the shape factor dF'_{x_0-x}, equation (4), which was derived in an earlier paper for a unit area at (x_0) and a strip of differential

$$dF'_{x_0-x} = \frac{h^2 dx}{2[h^2 + d^2]^{3/2}} \text{ rectangular configuration} \quad (4)$$

width parallel to each other but on opposite parallel walls, and

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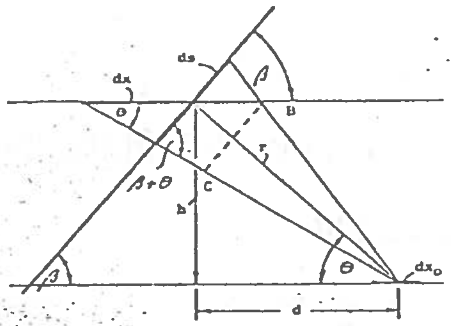

Fig. 2 Nomenclature for configuration factor determination

using the nomenclature, as shown in Fig. 2, the corresponding factor dF_{x_0-x}, equation (5), for the sinusoidal configuration is obtained.

$$dF_{x_0-x} = \frac{[(x_0 - x)\sin x_0 + (\cos x_0 - \cos x)]\,[(x_0 - x)\sin x + (\cos x_0 - \cos x)]dx}{2m[1 + m^2 \sin^2 x_0]^{1/2} \left[\left(\frac{x_0 - x}{m}\right)^2 + (\cos x_0 - \cos x)^2\right]^{3/2}}$$

sinusoidal configuration (5)

Now substituting equation (5) into equation (2) $\rho a(x_0)$ can be evaluated if a functional distribution for $\rho a(x)$ is assumed. Successive iterations have to be made until $\rho a(x_0)$ for every point falls upon the originally assumed and step by step corrected $\rho a(x)$.

In this manner the apparent reflectivity distribution $\rho a(x)$ in the sinusoidal fold is determined.

Then by summing or integrating over the fold from $-\pi$ to $+\pi$, the apparent reflectivity ρa_d of the drapery for diffusely incoming radiation is obtained from equation (6).

$$\rho a_d = 1 - \frac{1-\rho}{2\pi\rho} \int_{-\pi}^{\pi} \rho a(x) \sqrt{1 + m^2 \sin^2 x}\, dx \qquad (6)$$

The calculations indicated previously, involving considerable trial and error, for any specific case can best be carried out with a large scale digital computer.

As an example for a length over width ratio s/x for the fold of 2, which gives an m of 2.6, and for a flat material reflectivity of 0.25, the apparent reflectivity becomes 0.17.

B. Parallel Ray Incident Radiation

From Fig. 3 it can be seen that in the case of parallel ray incident radiation part of the fold receives direct radiation while the rest receives only diffusely reflected radiation as before. If s is taken as the energy of the incoming beam of radiation, per unit area and unit time and perpendicular to the beam, the radiosity can again be defined as shown in equations (7), (7a), and (7b).

$$B(x_0) = \rho H(x_0) \qquad (7)$$

$$= \rho\left[s \sin\gamma + \int_{x_1}^{x_2} B(x) dF_{x_0-x}\right] \qquad \begin{matrix} x_2' < x_0 < \pi \\ -\pi < x_0 < x_1' \end{matrix} \qquad (7a)$$

$$= \rho \int_{x_1}^{x_2} B(x) dF_{x_0-x} \qquad x_1' < x_0 < x_2' \qquad (7b)$$

Letting $B/S = \beta$ these equations become:

$$\beta(x_0) = \rho\left[\sin\gamma + \int_{x_1}^{x_2} \beta(x) dF_{x_0-x}\right] \qquad \begin{matrix} x_2' < x_0 < \pi \\ -\pi < x_0 < x_1' \end{matrix} \qquad (8a)$$

$$\beta(x_0) = \rho \int_{x_1}^{x_2} \beta(x)\, dF_{x_0-x} \qquad x_1' < x_0 < x_2' \qquad (8b)$$

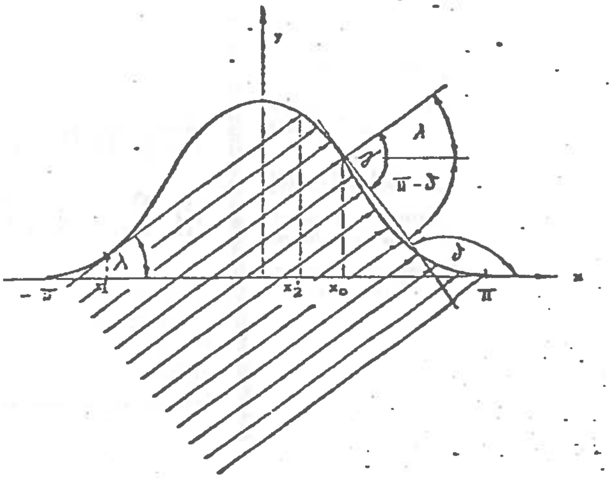

Fig. 3 Configuration and nomenclature for parallel ray incident radiation

with

$$\sin\gamma = \frac{+m \sin x \cos\lambda + \sin\lambda}{\sqrt{1 + m^2 \sin^2 x}} \qquad \gamma = (\pi - \delta) + \lambda \quad (9a)$$

$$\sin\gamma = \frac{-m \sin x \cos\lambda - \sin\lambda}{\sqrt{1 + m^2 \sin^2 x}} \qquad \gamma = \delta - \lambda \quad (9b)$$

$\beta(x_0)$ is evaluated in the same manner as $\rho a(x_0)$ was evaluated in part A, again requiring a number of iterations until every calculated value of $\beta(x_0)$ falls upon the function $\beta(x)$.

Having the correct function $\beta(x)$ the apparent reflectivity ρa_D for direct incident radiation can now be calculated from equation (10).

$$\rho a_D = 1 - \frac{\text{absorbed and transmitted energy}}{\text{incident energy}}$$

$$= 1 - \frac{\frac{1-\rho}{\rho}\int_{-\pi}^{\pi} B(x)dx}{2\pi\, S \sin\lambda} \qquad (10)$$

$$= 1 - \frac{1-\rho}{2\pi\rho \sin\lambda} \int_{-\pi}^{\pi} \beta(x) \sqrt{1 + m^2 \sin^2 x}\, dx$$

Again choosing an example for a drapery which has a reflectivity of 0.25 for the flat material at an angle of incidence of 55 deg. If the horizontal projection of the angle of incidence is 45 deg, the value for the apparent total reflectivity for parallel ray incident radiation becomes 0.04.

Apparent Reflectivity of the Drapery

Combining the results obtained previously for diffusely incoming radiation and for direct beam radiation and knowing the intensity of the direct radiation I_D and that of the diffuse radiation I_d the fraction of incoming direct radiation F_D can be calculated

$$F_D = \frac{I_D}{I_D + I_d} \qquad (11)$$

and the apparent reflectivity of the drapery is obtained from equation (12).

$$\rho a = F_D(\rho a_D) + (1 - F_D)(\rho a_d) \qquad (12)$$

Now returning to the numerical example and assuming that 60 percent of the total incoming radiation is direct then

$$\rho a = 0.6(0.04) + 0.4(0.17) = 0.092$$

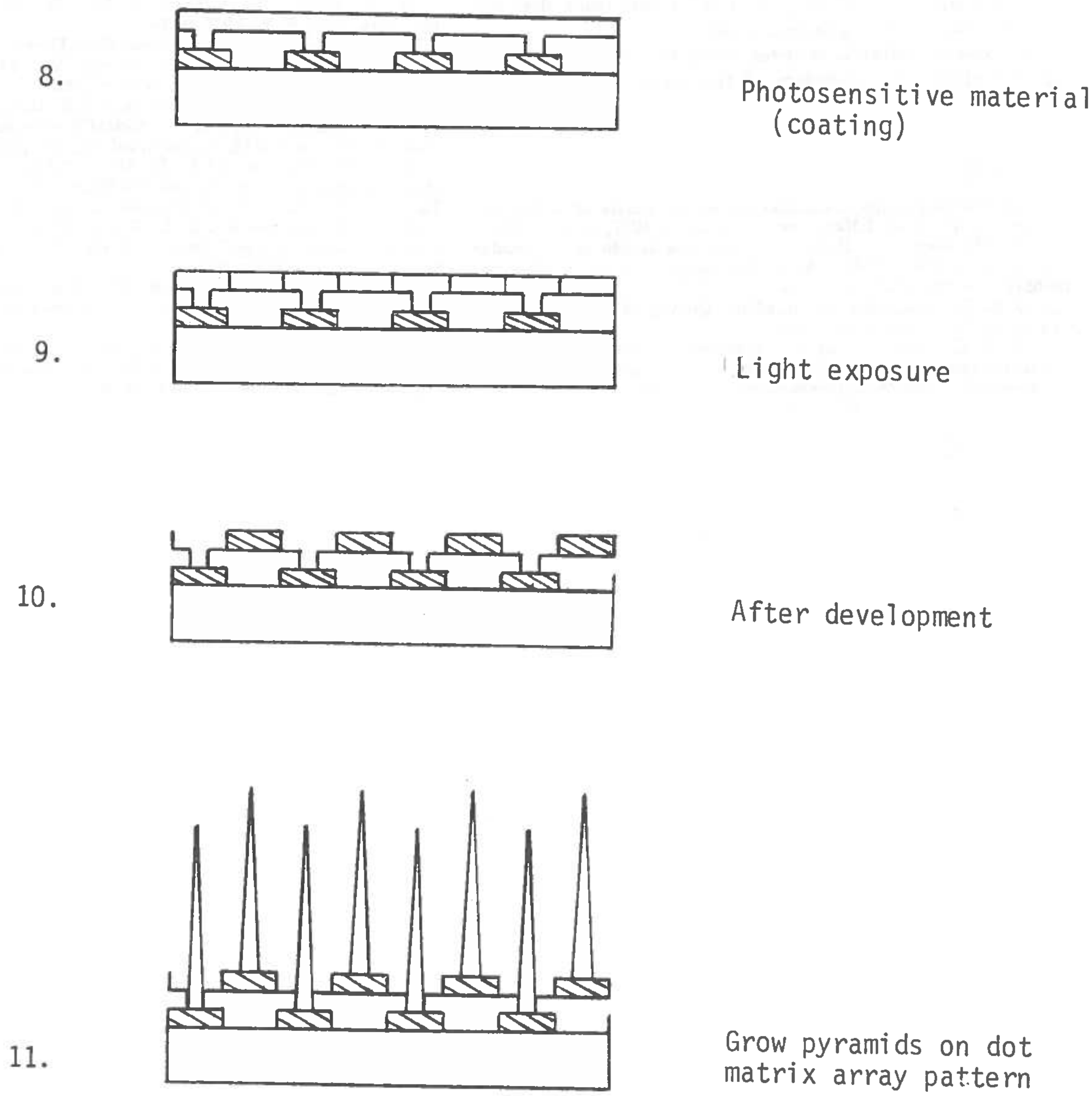

Figure 72. ASETEC Manufacturing Sequence

From previous work both theoretically and experimentally it is observed that the energy which is not reflected is absorbed and transmitted and thus becomes part of the heat gain. So for this reason separation of absorption and transmission does not seem necessary for heat-gain calculations.

If it becomes desirable, however, to separate the transmission and absorption, the procedure of the previous paper can be followed.

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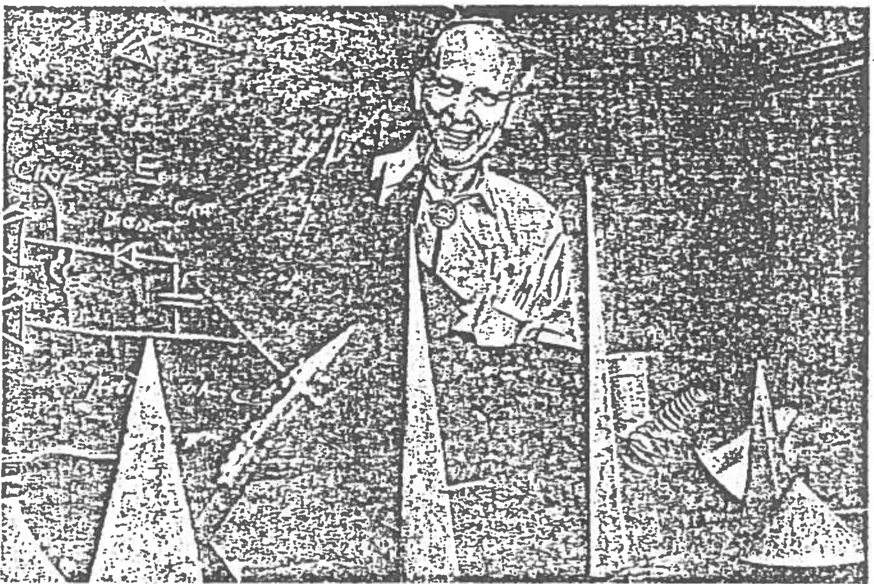
Printed in U. S. A.

OF MATERIAL INTEREST

FARBER

A tip from nature



In the insect world, males of some species use their antennae to help find their mates by sensing infrared radiation emitted by the female. Letting nature be the guide, scientists at the University of Florida are experimenting with antennae to harness solar energy as an alternative to using solar cells. For nearly 40 years, Professor Erich Farber, an expert on solar energy, has studied the use of various geometric shapes to convert solar energy to other forms of energy. With funding from the Air Force, Dr. Farber is incorporating research work (how insect's antennae pick up infrared signals) of two other UF professors into his research on antennae that will outperform solar cells (photovoltaics).

Key problems include determining the most efficient antenna configuration to convert electromagnetic waves to electrical energy, and the most efficient combination of antenna shape and coupling between antennae. Nature uses dozens of shapes, most corresponding to different kinds of manmade antennae such as the sloped array of a TV antenna. So far, researchers have looked at cones, pyramids, and dipoles; pyramids appear to be the best shape because the bases of pyramids can be packed close together to catch all the light falling on an area.

Antennae that will respond to the frequency spectrum of visible light (1000s of GHz) need to be very small. Farber has obtained electric current from inexpensive modified sandpaper, where the pyramid-shaped carborundum (SiC) crystals on the sandpaper act as antennae. Sandpaper was used to convert light waves to electrical energy by shining light from a car headlamp connected to a dc power supply onto the sandpaper. However, the energy-conversion efficiency of this process is not high because the crystals on the sandpaper have a random orientation; the ideal situation is to have all the crystals packed close together on their pyramid bases. Further research is needed to find out how to grow crystals of the required size, how to pack them properly, and how to couple crystals together.

According to Farber, nature's technique has more promise for harnessing the sun's power than solar cells, which have a built-in limit on how much solar energy they can trap. For example, the best commercial solar cells operate at about 15% efficiency, and the best energy-conversion efficiency may be only 25 to 30% due to a fundamental limitation in photovoltaic technology. By comparison, antennae have no theoretical efficiency ceiling and the conversion efficiency can be as high as 60 to 85%.

As a by-product of the solar-energy research, antennae also may prove useful for energy conversion in the microwave range (0.7 to 10 GHz) — producing electrical power from microwaves beamed to remote locations. For example, on a makeshift runway, individual lights containing a microwave antenna could be lit by microwaves beamed from a central power source. The process also may prove useful for stealth aircraft. Since antennae absorb energy, the surface of a bomber that is textured into an array of antennae that absorb radar waves would make the aircraft invisible to radar scanners.

The Editors

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Queen's University
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August 5, 1987

Professor E. Farber
Physics Department
University of Florida
Gainsville, Florida 32611
U.S.A.

Dear Professor Farber,

Having read your article in Advanced Materials and Processes/Metal Program 7/87, I write to inform you that we can produce, by sputtering of copper with 40 keV argon ions, precisely the pyramidal structures you suggest. These are of micrometre dimensions. A copy of a micrograph is enclosed to give you some idea of the features. This is on a polycrystal, but when a properly oriented single crystal is used, the entire surface becomes covered with octagonal facetted pyramids which, when viewed in daylight, reflect only red.

Please write or phone if you want further information.

Yours truly,

Jim Whitton

J.L. Whitton
Professor of Physics
Tel. No. (613) 545-2697
OR (613) 545-2672

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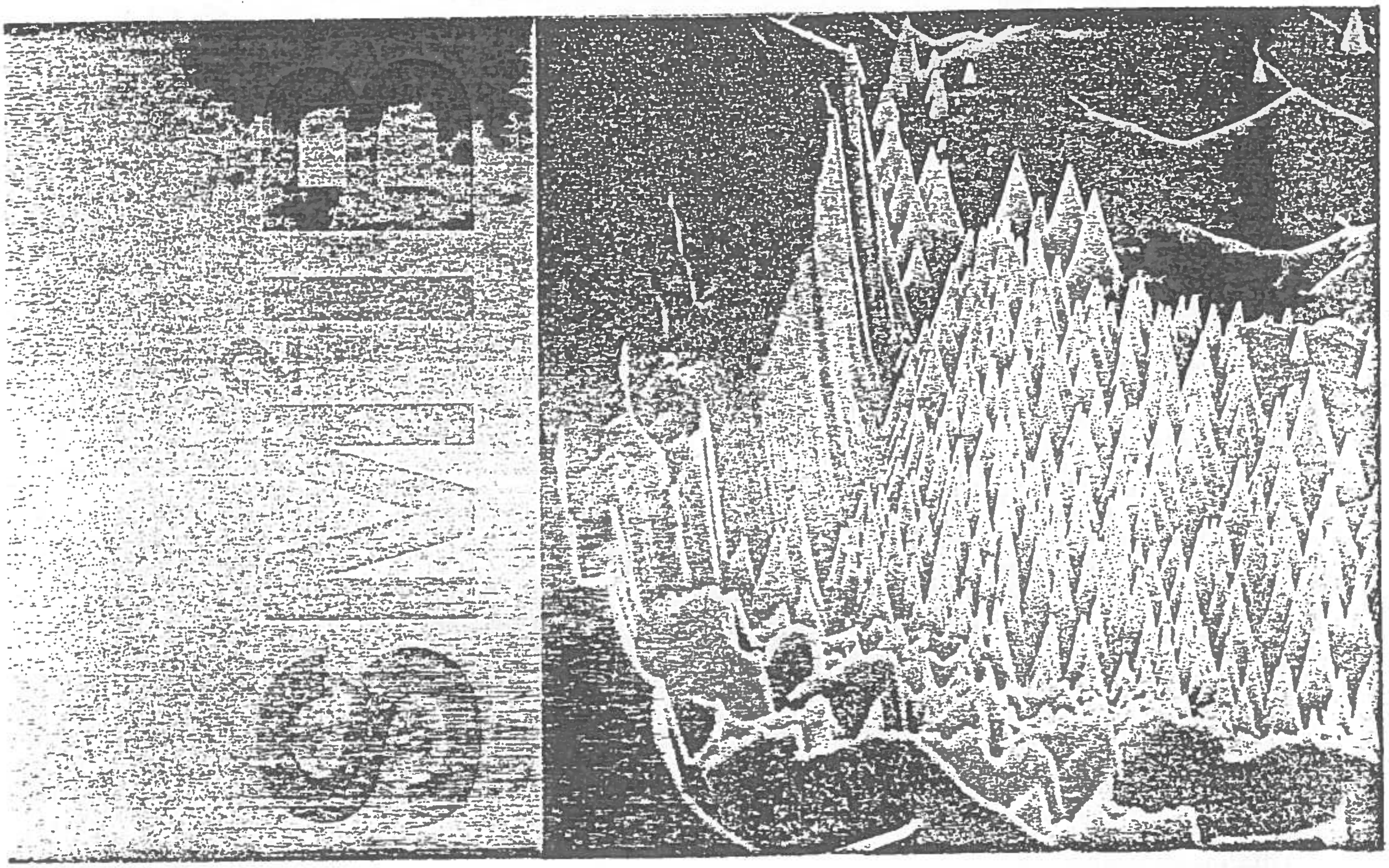
International Conference on Surface Modification of Metals by Ion Beams



ABSTRACTS

Queen's University at Kingston

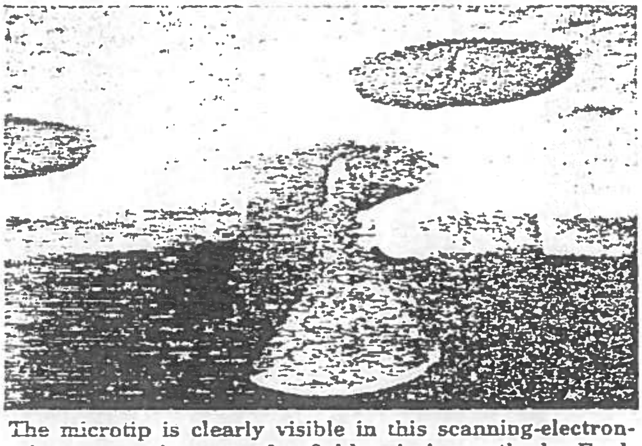
MICROTIP TV

This new flat-screen display, made by the same techniques used in microcircuit manufacture, will offer many advantages: high-resolution image, low energy consumption, and good reliability. The first projected use of microtip technology: an avionics display for the cockpits of coming Boeing Co. aircraft.

By NAOMI J. FREUNDLICH

MENLO PARK, CALIF.

I focus intently on the black-and-white photos, trying to identify their subjects. One of the images appears to be a close-up of Swiss cheese with little upside-down golf tees inside the holes. The other looks like a piece of perforated board. Charles (Capp) Spindt, a senior researcher at the physical electronics laboratory of SRI International, explains the details. Rather than being dairy-based, the pitted material is made of silicon. And the golf tees are actually tiny electron guns, captured on film by a scanning electron microscope. The perforated board is an array of these guns. According to Spindt, 1,000 electron guns, or microtips, will someday be packed into a single TV picture element, or pixel, making a super-sharp image in a flat-screen display possible.



The microtip is clearly visible in this scanning-electron-microscope close-up of a field-emission cathode. Each niobium-metal-rimmed hole is only one micron wide.

The uses for these microscopic electron sources, named Spindt cathodes for their inventor, are varied. Currently, SRI is developing arrays of microtips for a sophisticated color avionics display to be used in Boeing Co. aircraft starting in 1992. The specifications call for a 6¾-by-6¾-inch screen less than an inch thick. In France, at the Laboratoire d'Electronique et de Technologie de l'Informatique, in Grenoble, scientists have already built elementary 0.4-inch-thick flat panels using microtip technology. The goal is to develop a bright high-resolution image at a lower cost and energy demand than those of previous flat-screen technologies.

The original impetus to develop Spindt cathodes was NASA's need for less-power-hungry, lower-temperature electron sources in communication satellites. Thermionic cathodes, found in ordinary TV cathode-ray tubes (CRTs), emit electrons only when heated to high temperatures. Spindt cathodes are based instead on the field-emission effect. Here, a strong electric field draws electrons from the tip of a metal cone. Spindt cathodes can operate at temperatures ranging from that of liquid nitrogen, −195 degrees C, to 600 degrees C, and use substantially less energy. Spindt predicts that his so-called cold cathode tubes may use 25 percent less energy than does a comparable thermionic electrode device. Also, less waste heat is generated.

Only one micron, or 1/25,000 inch, high, these cathodes are a product of advanced micro-fabrication techniques similar to those used to make computer chips. "We've come full circle with this technology," says Spindt. "Micro-fabrication techniques allowed us to replace bulky CRTs with solid-state devices. Now those same techniques are allowing us to build vacuum cathodes that, for all intents and purposes, could be better than those solid-state devices."

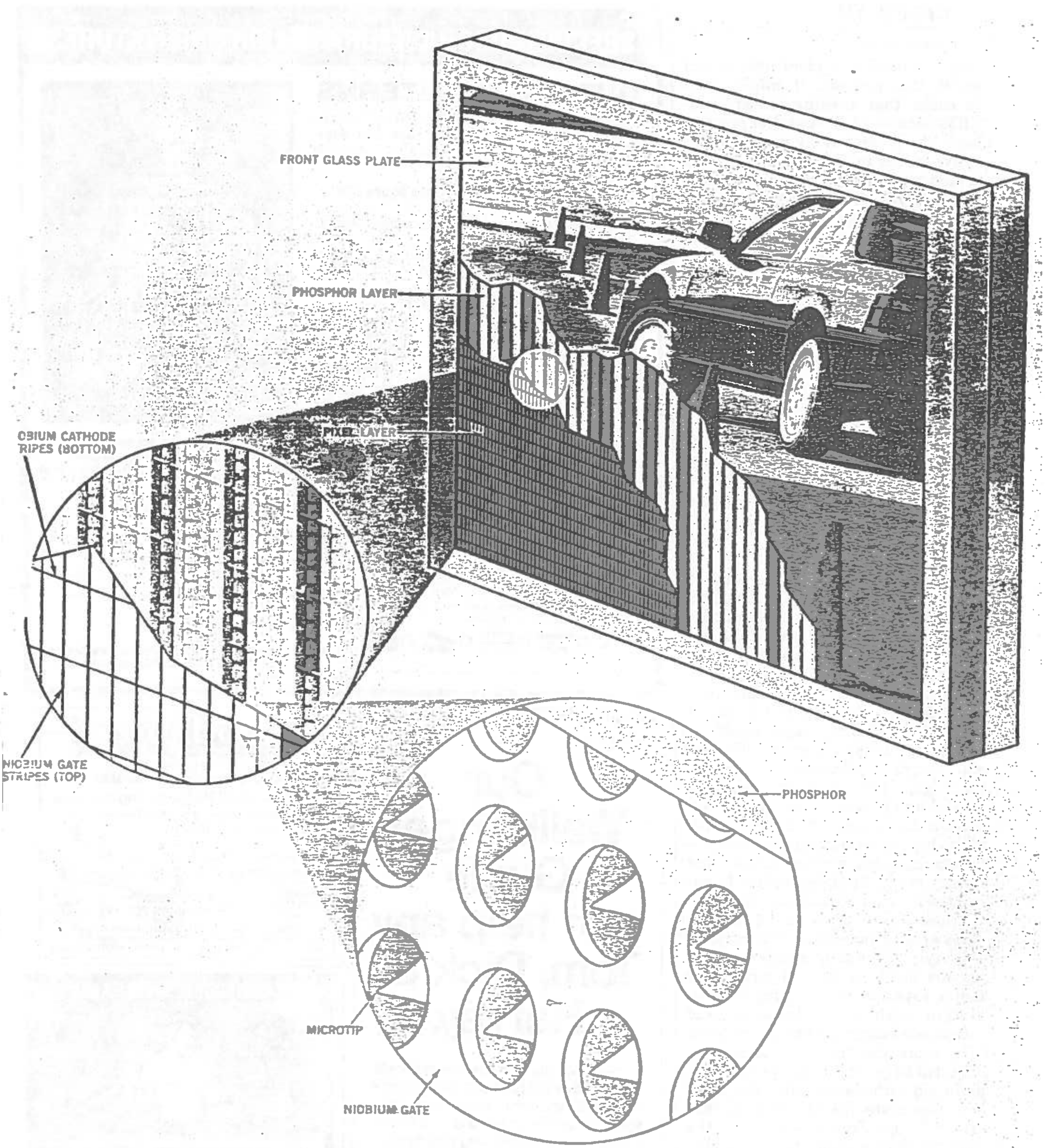
Spindt likens the cathode fabrication process to making a sandwich—one slice of silicon (a conductor), one of silicon dioxide (a dielectric), and a final layer of molybdenum (a metal conductor). The single-micron Swiss-cheese holes are formed by selective etching processes that carefully eat through the layers.

"We make the cathodes so small to keep power consumption low," says Spindt. "The way to get that is to have the metal electrode very close to the emitter tip." The reasoning is that the electric field strength can be increased not only by applying more voltage but also by keeping the metal electrode close to the tip and concentrating the charge.

Creating that tip—which at its thinnest point is only about 300 angstroms, or 100 molecules, thick—proved to be the trickiest part. In a vacuum chamber the Swiss-cheese array, appearing only as a ½-inch stud, rotates on a pedestal. A small chamber holding aluminum oxide is aimed at the stud from a 30-degree angle. A second chamber holding molybdenum is aimed straight at the substrate. As the stud rotates, the aluminum oxide is evaporated on the walls and top surface of each hole, gradually closing it up. The molybdenum is phased in, and as the hole gets smaller a sharp metal peak forms inside. The last step is to selectively etch away the aluminum oxide, leaving the final structure, a microtip. Growing the microtips is a parallel process because every hole on the stud experiences the same molybdenum buildup at the same time.

"If we can make them cheap enough, these mini-cathodes could replace the cathode-ray tube in the TV set in everyone's home," predicts Spindt. "There should be no difficulty,

[Continued on page 89]



A color microtip screen would work as follows: At each pixel (the area where the niobium stripes overlap) there would be three separate phosphor strips (red, green, and blue) in close proximity to each other. The top stripes, or lines, of niobium are very close to these phosphors (only 50 microns away), which eliminates the need for focusing. Five hundred lines will run horizontally, each connected to several rows of microtips. Perpendicular to this will be three times that many (1,500) lines addressing the gate electrode, the electrode that actually extracts electrons from the microtips. Thus, in each pixel there will be three groups of gate electrodes, one for each color.

To turn on a given line, you would first apply a negative voltage to one of the 500 horizontal lines connected to a row of microtips. Making the microtips negative makes the phosphor front plate (where you want electrons to go) positive with respect to the microtips. The field-emission cathode has a sharp turn-on threshold, and the negative bias brings it up to the limit. A small positive voltage applied to the gate lines pushes the cathode over threshold and causes emission, turning on whichever one of the three colors or combination of three colors you wanted illuminated. With this arrangement, an entire row can be turned on at a time, rather than just one pixel.

Microtip TV

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once the market is identified, to tool up to this process. It might even be easier than making conventional CRTs because of the parallel processing." The largest array made to date is five inches in diameter. "The limit is having the molybdenum source far enough away that it looks like a parallel beam coming in," says Spindt, the way the sun is always in the same spot as you drive down a road.

The other limit is the cost of silicon wafers large enough to build a full-size flat screen. The French approach —originally used by SRI—starts with a glass substrate to overcome this problem. Because glass is not conductive, it must be covered with a thin film of niobium metal. This film is patterned into narrow stripes across the glass, and a dielectric layer of silicon dioxide is deposited on top. Stripes of niobium metal running crosswise to the first stripes (see drawing) form the fourth layer.

Brightness counts

A full-color screen, according to Spindt, will have as many as 1,000 microtips per pixel. This keeps picture quality high even if a few of the microtips malfunction. Maintaining brightness is especially important for an avionics display. "You might take a quick turn and get full sunlight right at the display," says Spindt. "If you've ever taken a portable TV outside, you know what it's like. The picture's gone just when you needed a crucial bit of information." As for resolution, Spindt says it could be possible to have lines only microns apart—approaching one emitter tip per line —but that kind of resolution is not needed for current applications.

There are other flat-screen technologies around, including liquid-crystal displays, vacuum fluorescents, and plasma displays, but all have their faults, says Spindt, including low resolution, high power demands, and complicated electrode matrix systems. "The more you try to do something different to get the same result as the plain old cathode-ray tube, the more you appreciate the elegance of that critter," says Spindt. But with the microtip display, SRI might just surpass those results.

Other uses for Spindt cathodes could include electron microscopes, mass spectrometers, and free-electron lasers. Eventually tiny vacuum-tube circuits could be used as a higher-speed, heat-and-radiation-resistant alternative to solid-state integrated circuits; electrons move faster in a vacuum than in a solid-state medium. Spindt also thinks that microtip displays may enter the auto market. PS

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